CUSTOMER SUITABILITY OF ELECTRIC VEHICLES BASED ON BATTERY-STATE-OF-CHARGE ANALYSIS

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Abstract

Based on German driving profiles, the paper analyses technical restrictions of EV batteries and their implications for the suitability as EVs. Minimal & maximal battery SOC curves serve as an indicator for the behavior of EV batteries. In 3 scenarios, charging infrastructure developments are compared with electric ranges. It is shown that from a technical point of view range anxiety is negligible. Furthermore, infrastructure development has a bigger impact on the suitability than battery sizes.

Introduction

Current discussions regarding the future of electric mobility try to find answers for the necessary and useful capacity of the battery of electric vehicles. Furthermore, the interaction with the power grid and the implications for the battery-size are yet to be answered. The work to be presented analyzes the technical restrictions affecting the state-of-charge of batteries and hence their actual required capacity, based on real world driving patterns. Our aim is to provide indicators to which extent the battery size and the infrastructure development influence these technical restrictions. Eventually, the suitability of electric vehicles for German driving patterns will be analyzed based on varying assumptions for the development of charging infrastructure and battery capacities.

Methodology of the battery state of charge analysis

In order to quantify user behavior and driving patterns, a new approach has been developed. Based on the comprehensive survey “Mobilität in Deutschland (MiD) 2008” with over 34,000 surveyed vehicles and more than 193,000 trips, driving profiles have been analyzed in detail ([1]). The available profiles have been preprocessed into individual profiles with an hourly resolution regarding their driving status. These profiles incorporate information about the driven distance, the travel time, and the purpose of the trip. The purpose of the trip will be used in the following steps in order to quantify the availability of an unoccupied charging spot at the end of each trip. Table 1 shows the assumptions made regarding the charging infrastructure.[1]

Purpose of trip	Work	Education	Business	Escort	Private Business	Shopping	Leisure	Other	Home
P(x)	50%	40%	10%	10%	10%	30%	30%	10%	70%

Table 1: Assumptions for the availability of an unoccupied charging spot at the end of each individual trip, depending on the purpose of trip

Six types of electric vehicles have been specified: small, medium, and large sized battery electric vehicles (BEV) as well as range-extended vehicles (EREV). The vehicles have been defined and simulated in an earlier paper, using real world driving cycles[2] ([2]). Table 1 summarizes the assumptions made for the vehicles. In order to produce realistic results, the upper and lower boundaries of the usable battery capacity have been adjusted to incorporate the fact that batteries will neither be charged up to 100% nor be discharged down to 0%. According to currently introduced vehicle concepts, the usable battery capacity for BEVs is anticipated to range from 10% to 95% of the actual physical capacity, whereas the EREV batteries will be used in the range of 35% to 90% ([3, 4, 5]).

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[1] For a detailed definition of the trip-purposes taken into account, see ([1]).

[2] Specifically, the three Artemis cycles ‘Urban’, ‘Road’ and ‘Motorway’ have been combined using a set distribution.

2010		BEV			EREV		
		small	medium	large	small	medium	large
Battery capacity	**[kWh]**	24.3	45.9	62.1	16.2	18.9	24.3
Upper limit for usable capacity x_1	**[%]**	95%	95%	95%	90%	90%	90%
	[kWh]	23.1	43.6	59.0	14.6	17.0	21.9
Electrical range	**[km]**	139.6	205.3	208.6	60.2	58.1	56.4
Lower limit for usable capacity x_2	**[%]**	10%	10%	10%	35%	35%	35%
	[kWh]	2.4	4.6	6.2	5.7	6.6	8.5
	[km]	16.4	24.2	24.5	38.3	37.0	35.9
Energy consumption	**[kWh/100km]**	14.8	19.0	25.3	14.8	17.9	23.7

Table 2: Characteristics of the utilized electric vehicles.

Using the individual profiles regarding trip-mileages and trip-purposes, two different state-of-charge boundaries for the vehicles' batteries have been calculated for each electric vehicle type. The two state-of-charge boundaries represent the maximum and the minimum feasible charging patterns of the vehicles. The maximum state-of-charge function (blue curve) results by assuming that the batteries will be charged at the maximum available power level of 3.7 kW as soon as the vehicles are plugged-in, whereas the minimum state-of-charge function (red curve) ensures that the last trip of day will be feasible taking into account possible grid-contacts during the day. In other words, the maximum line indicates uncontrolled charging, whereas the minimum line illustrates the available range to use the batteries of electric vehicles as controllable loads or storage units for electric energy. Ergo, both lines represent the upper and lower technical limits as to how batteries of electric vehicles might be utilized. Figure 1 illustrates the methodology applied to the driving profiles recorded in the MiD 2008 database. ([6])

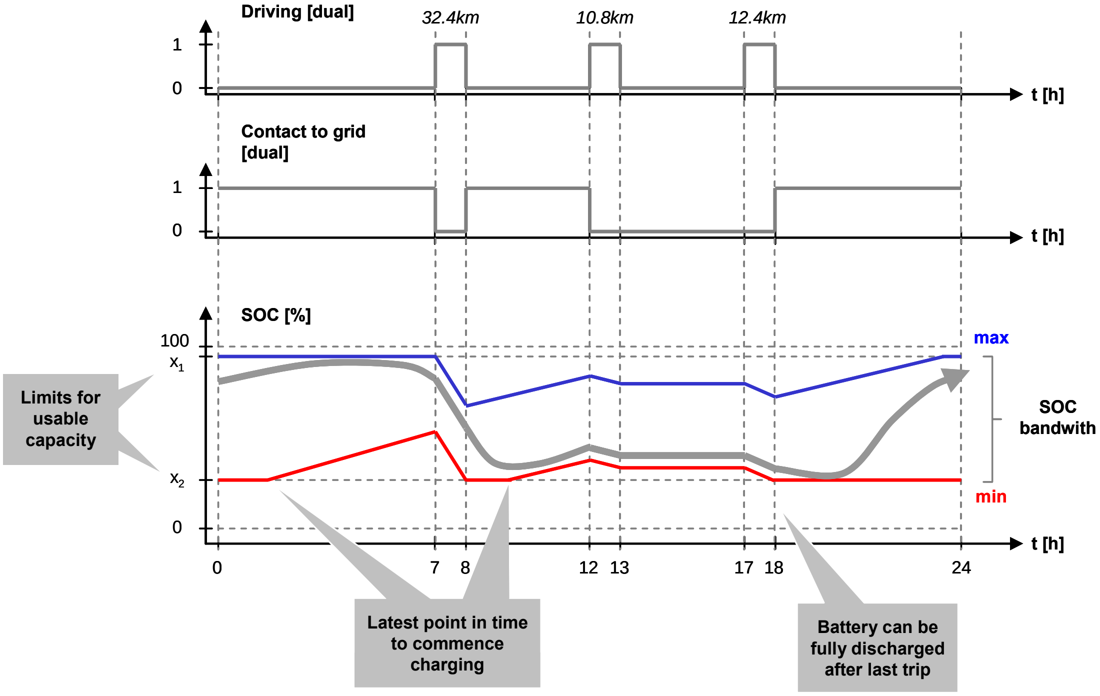


Figure 1: Methodology for the calculation of state-of-charge boundaries.

Based on the calculation of the minimum and maximum state-of-charge functions for each vehicle concept, the different boundaries have been superposed in order to allow statements about the charging pattern of the entire vehicle fleet. Density functions for the state-of-charge have been deducted using cumulative distribution functions. As a result, the state-of-charge boundaries can be analyzed choosing a freely selectable significance level and hence limiting possible calculation errors.

The utilization of this methodology in combination with the comprehensive MiD 2008 data generates statistically significant statements. Figure 2 summarizes the methodology applied.

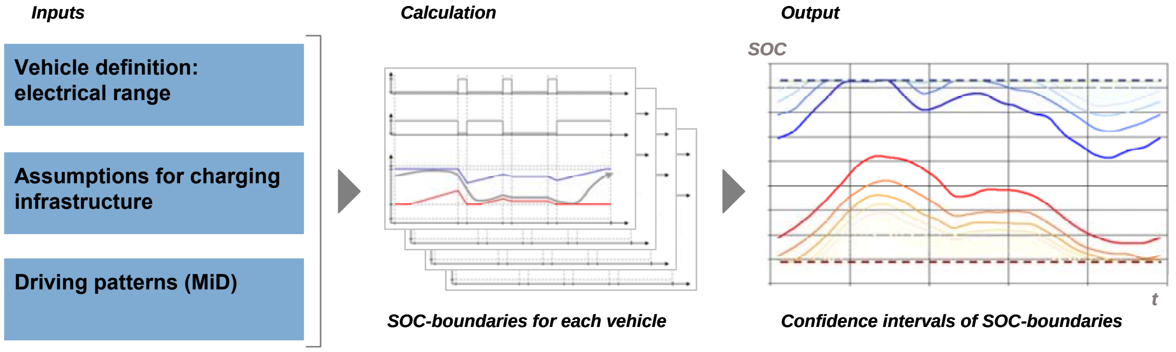


Figure 2: Methodology for the calculation of confidence intervals of SOC-boundaries.

State-of-charge boundaries for electric vehicles

Figure 3 shows exemplary results for the state-of-charge confidence intervals for medium battery electric vehicles. The gap between the maximal state-of-charge boundary (blue curve) and the minimal feasible state-of-charge (red curve) represent the actually usable capacity of the battery at any given time. For the issue of load leveling of the power grid or even vehicle-to-grid applications, the ‘area’ between these 2 boundaries represents the capacity that could be used for controlled charging / discharging.

Considering a high significance level of 99%, three key learnings can be derived from the state-of-charge boundaries: First, the narrowest gap between the maximal available and the minimal required state-of-charge occurs in the morning around 9 a.m. Second, at this very high confidence level, charging has to commence at 2 a.m. in order to give drivers the chance to reach their last destination of the day. And third, in the evening at around 8 p.m., only half of the battery is available for energy storage purposes. At this time, the load for the electric grid will significantly increase in case only uncontrolled charging will take place.

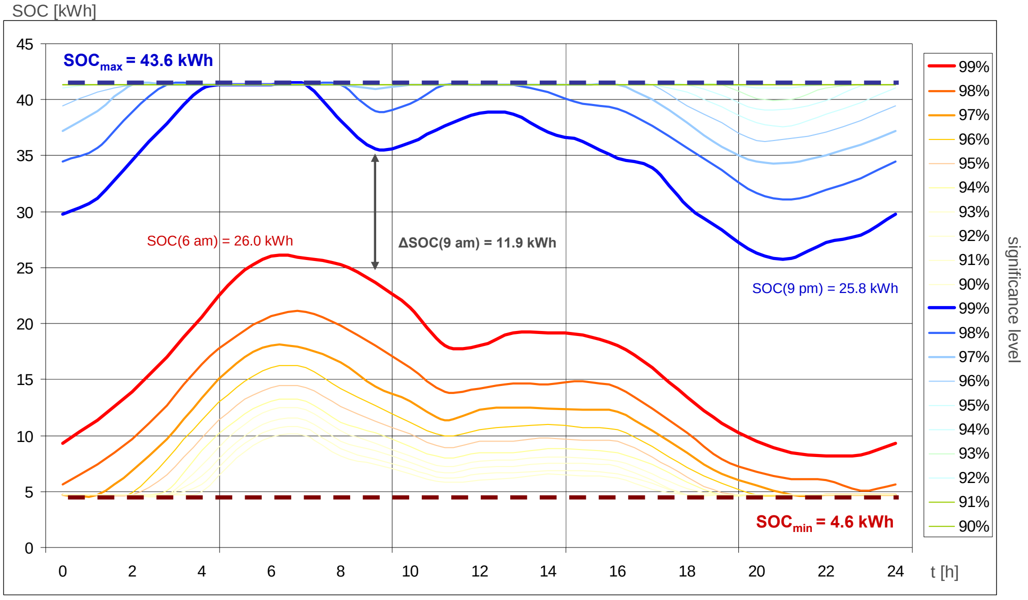


Figure 3: Confidence intervals for state-of-charge boundaries for the medium battery electric vehicles.

Since the analysis is based on each individual driving profile of the surveyed vehicles, detailed statements about the suitability of the driving profile for electric vehicles are feasible, taking into account the possibility of charging during the day at different locations. The results shown above indicate a somewhat restricted utilization pattern for electric vehicles. In order to be suitable for electric driving, the lower boundary of the charging profile of a given vehicle must not cross the upper boundary at any time. Under the assumptions described above for battery capacities and energy consumptions as well as for the charging infrastructure, the overall suitability for battery electric vehicles lies around 75% for all vehicles. In other words, three quarters of the surveyed vehicles might be driven fully electric under the assumptions made. However, questions regarding the influence of the charging infrastructure, the vehicle characteristics themselves, or even the range-anxiety of customers on the overall suitability for electric vehicles arise.

Suitability of electric vehicles for German driving patterns

In order to give answers to these questions, 3 different scenarios for the development of charging infrastructure have been calculated. When considering the vehicle characteristics such as the usable upper and lower battery-limits x_1 and x_2 or its energy consumption, the crucial indicator for a given vehicle is the ratio between these two indicators, also known as the electrical range. Furthermore, the limit x_2 might be interpreted as the range anxiety of a customer and hence be varied in order to quantify the influence of risk aversion on the suitability of electric vehicles. The 3 calculated scenarios compare different levels of deployment of charging infrastructure with different electrical ranges. The assumptions for the charging infrastructure have been varied regarding the probabilities for finding an unoccupied charging spot at the end of the trip. Additionally, a differentiation of the driving profiles regarding their urban structures has been made. The MiD 2008 database provides detailed information on 7 different types of urban development, ranging from metropolitan to rural areas. In the second scenario, the probabilities for charging have been varied depending on these 7 types of urban development. The last scenario analyzes a future in which charging will only take place at home. In other words, the consequences of no public charging infrastructure being build up are evaluated.
Figure 4 depicts the methodology used for the scenario calculations. Based on the algorithms for the calculation of the upper and lower SOC-boundaries (see figures 1 and 2) the input parameters have been varied. For each scenario, several electrical ranges as well as different assumptions regarding the charging infrastructure development have been taken into account. Based on a detailed analysis of the SOC-boundaries for each surveyed vehicle, the resulting rates for the suitability as EV have been depicted in one chart, utilizing differently colored curves for different infrastructure deployment stages.

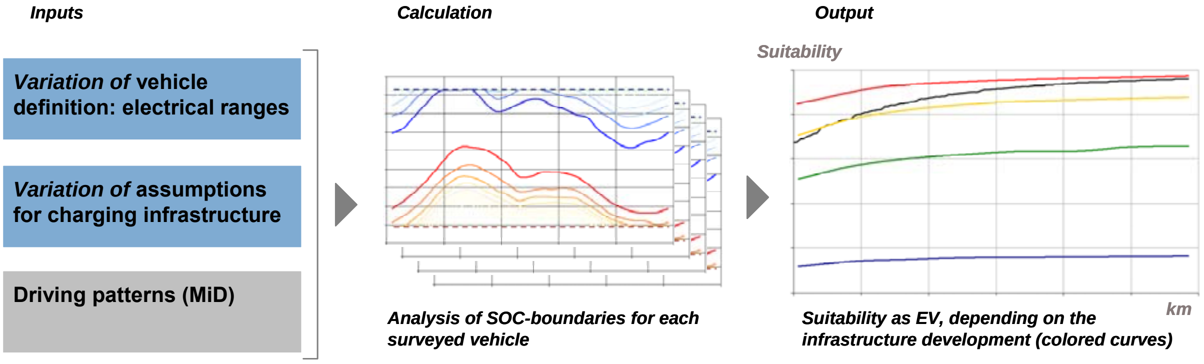
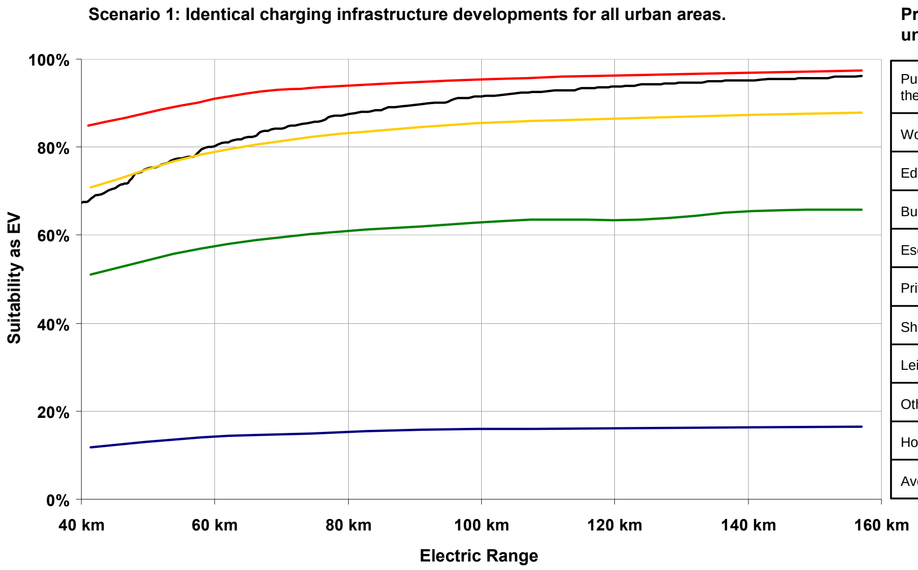


Figure 4: Methodology for the calculation of the rate for the suitability as EV.

Scenario 1: Identical infrastructure development for all urban areas

The first scenario assumes identical charging probabilities for all types of urban areas. Figure 5 shows the suitability as electric vehicle (EV) depending on the electrical range and on the development of the charging infrastructure. As described above, the blue, green and yellow lines represent different set-ups of charging infrastructure and might be interpreted as a development over time. The red line serves as a comparison to a 100% charging infrastructure set-up assuming that customers will find an unoccupied charging spot after each trip. The black line depicts the empirical distribution function of German trip distances. On the right, the underlying probabilities depending on the purposes of the trips are given. The average figures represent the average of the probabilities weighted with the number of trips completed.



Probabilities for finding an unoccupied charging spot

Purpose of the trip	blue	green	yellow	red
Work	10%	39%	60%	100%
Education	10%	39%	60%	100%
Business	0%	6%	10%	100%
Escort	10%	57%	90%	100%
Private	5%	8%	10%	100%
Shopping	5%	43%	70%	100%
Leisure	10%	22%	30%	100%
Other	0%	6%	10%	100%
Home	10%	57%	90%	100%
Average	9%	44%	68%	100%

Figure 5: Scenario 1: Suitability as EV depending on the electrical range, assuming identical charging infrastructure developments for all urban areas.

Three major observations can be derived from this analysis:

First, taking into account only the vehicle miles traveled (VMT) per day (black curve) when trying to figure out which electrical range serves the customer best will cause significant deviations. For electrical ranges above 100 km, the VMT-curve lies closer to the 100% scenario (red curve) than to the yellow line, even though this curve does already represent an optimistic development of the charging infrastructure.

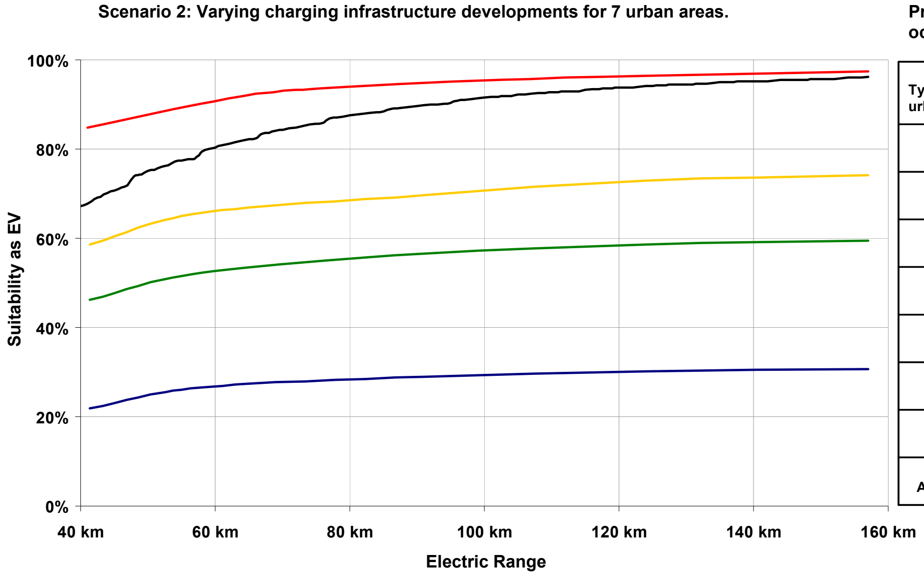
Second, the availability of charging infrastructure is significantly more important than the electrical range. In other words, increasing the average availability of charging infrastructure from 9% to 44% (times 5) has a significantly higher impact on the suitability of EVs than increasing the all electric range from 40 km to 200 km (times 5, too). Furthermore, the suitability as EV shows only a weak dependence on the *average* infrastructure availability. The curves for all 3 infrastructure set-ups (blue, green, yellow) lie significantly above their corresponding weighted averages – for all electrical ranges.

Third, from a technical point of view, the question of range anxiety plays only a minor part. As described above, the electrical range represents the technically feasible range of the electric vehicle, assuming upper and lower limits for the usable battery capacity as well as real world driving cycles. The range anxiety might be interpreted as an additional electrical range which the vehicle has to provide in order to compensate for the risk aversion of the customer. Hence, the resulting available electric range might be derived from the chart by simply subtracting a certain amount from the maximal available electric range. For electric ranges of more than 100 km the slope of all curves decreases significantly. I. e., above a certain electric range the suitability as an EV shows only a weak dependence on the range itself. E. g., the suitability of a battery electric vehicle with a real world electric range of approximately 150 km decreases only marginally, even if the customer shows a strong range anxiety and prefers a security stock of 50 km or one third of the overall range.

Scenario 2: Varying charging infrastructure development for the urban areas

The fact that the availability of charging infrastructure seems to have a bigger impact on the suitability than the electric range of EVs itself points to the question where charging infrastructure should be build up. In order to analyze this issue, a second scenario has been calculated. This second scenario enhances the first scenario by additionally differentiating the development of charging infrastructure depending on the type of urban development. As mentioned above, 7 types of urban areas have been evaluated, ranging from metropolitan areas (type 1) with a very high population density to rural areas (type 7) with a very weak density.

Figure 6 shows the suitability of EVs for scenario 2. Again, like in the first scenario, the red curve serves as a 100% indicator, whereas the black curve represents the distribution function of the distances of all trips of German passenger cars. For the trip-purposes “Home” and “Escort” the probabilities for finding an unoccupied charging spot have been varied depending on the type of urban area. It has been assumed that the chance for finding a charging spot increases in rural areas. This accounts for the fact that vehicles in metropolitan areas usually are not parked at the same spot when returning home. For comparability reasons all other probabilities have not been changed. The blue, green and yellow curves again depict 3 different set-ups of charging infrastructure. Accordingly, the average again indicates the weighed average over all trips.



Probabilities for finding an un-occupied charging spot *at home*

Type of urban area	blue	green	yellow
1	10%	33%	50%
2	15%	41%	60%
3	20%	46%	65%
4	30%	53%	70%
5	40%	60%	75%
6	70%	82%	90%
7	80%	89%	95%
Average	19%	33%	45%

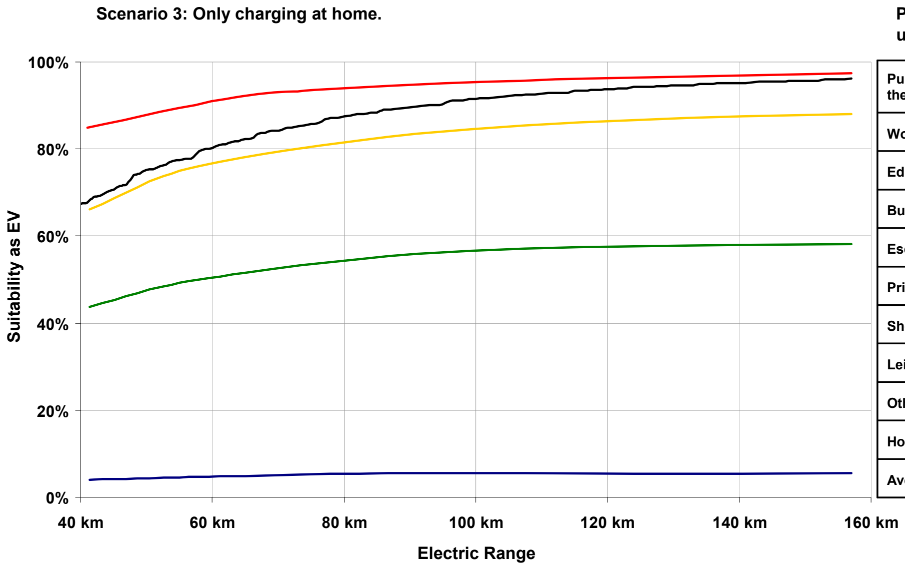
Figure 6: Scenario 2: Suitability as EV depending on the electrical range, assuming varying charging infrastructure developments for 7 types of urban areas.

Comparing the two scenarios shows that the three major observations made in scenario 1 also hold true for scenario 2: Analyzing only VMT causes deviations, charging infrastructure development is significantly more important than electrical range, and range anxiety is not as crucial as most customers anticipate. However, the second scenario indicates additional information about the suitability as EVs: It seems to be crucial *where* charging takes place. Although the yellow curve in the second scenario accounts for only 1 percentage point more than the green curve of the first scenario (45% vs. 44%), its suitability as EV lies significantly higher. A detailed analysis of the simulation results shows that this increasing suitability is caused by a high share of charging at home. In fact, with these assumptions made, rural areas show a significantly higher suitability for EVs than metropolitan areas do.

Scenario 3: Only charging at home

Since charging at home seems to have a significant impact on the suitability as EVs, a third scenario has been calculated, assuming that charging will only take place at home. Figure 7 depicts the results. In order to assess how important the infrastructure development is, again 3 different deployment stages of the charging infrastructure have been simulated (blue, green and yellow curve). Like in the first 2 scenarios, the red and the black curve have been added for comparability reasons.

Again, the theses derived in the first 2 scenarios seem to hold true for this scenario as well. Additionally, the importance of charging at home is being pointed out. Assuming a 100% chance for finding a charging spot when returning home nearly resembles the distribution of the trip distances of the entire fleet (black curve), although the weighted average of available charging infrastructure only sums up to 53%. In other words, by assuming that a customer who is willing to buy an electric vehicle will ensure that he is able to charge at home significantly increases the suitability of German driving profiles for EVs. With a real world electric range of around 150 km 9 out of 10 vehicles might be replaced by battery electric vehicles.



Probabilities for finding an unoccupied charging spot

Purpose of the trip	blue	green	yellow	red
Work	0%	0%	0%	100%
Education	0%	0%	0%	100%
Business	0%	0%	0%	100%
Escort	5%	61%	100%	100%
Private	0%	0%	0%	100%
Shopping	0%	0%	0%	100%
Leisure	0%	0%	0%	100%
Other	0%	0%	0%	100%
Home	5%	61%	100%	100%
Average	3%	32%	53%	100%

Figure 7: Scenario 3: suitability as EV depending on the electrical range, assuming only charging at home.

Conclusion

The paper analyses the technical boundaries of EV-batteries and their implications on the suitability of German driving patterns for the usage of EVs. Indications on the importance of electrical ranges and charging infrastructure developments are given. However, the analysis focuses on the technical examination of German driving behavior and does not give answers on how the customers' buying decision will evolve or whether long distance (holiday) trips could affect these buying decisions.

By matching real-world driving patterns with technical specifications of electric vehicles and charging infrastructure, technical requirements for the batteries' state of charge boundaries have been identified. By superposing all individual profiles of the surveyed German passenger car fleet, we derive the actually usable battery capacity. The gap between the minimal and the maximal boundary indicates the range that could be used for load leveling of the power grid or even for vehicle-to-grid applications. It has been shown that due to technical restrictions, the possibilities of utilizing electric vehicles for load leveling of the power grid have to be assessed very carefully.

Based on this methodology, the relationship between the availability of charging infrastructure, the electric range of the vehicles, and the suitability as electric vehicle for German driving profiles has been analyzed. By simulating 3 different scenarios of charging infrastructure deployment it has been shown that an assessment of the suitability as electric vehicles based on vehicle-miles-traveled alone leads to significant deviations. Additionally, it has been shown that from a technical point of view the issue of range anxiety and risk aversion of the customer only has a minor influence on the suitability as EV if the vehicles have a real world electrical range of more than 150km. Furthermore, it has been pointed out that the availability of charging infrastructure has a significantly higher impact on the suitability than the electric range itself. In this context especially the possibility of charging at home is crucial.

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