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Mileage electrification potential of different electric vehicles in Germany

Patrick Plötz[1], Simon A. Funke
Fraunhofer Institute for Systems and Innovation research ISI, Breslauer Strasse 48, 76139 Karlsruhe, Germany
[1]patrick.ploetz@isi.fraunhofer.de

Abstract

Electric vehicles (EV), both as battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) have noteworthy potential to reduce global and local CO_2 emissions. However, the fully exploitable potential depends on the actual vehicle kilometers travelled (VKT) that can be electrified. For BEV, the limited range excludes long-distance trips from electrification. For PHEV, long-distance trips are not excluded but the shorter electric driving range could reduce the miles electrified. The aim of the present paper is to compare the potential to electrify total VKT of BEV and PHEV. We use real-world driving data from several 780 German conventional passenger cars that are simulated as BEV and PHEV of different ranges. Furthermore, the CO_2 emission reduction potential of both technologies and the influence of battery sizes are analyzed, by combining electrified kilometers with CO_2 emission factors. We find PHEV to electrify more miles, both individual VKT as well as total VKT of the overall car fleet for given electric range. The difference in fleet electrification potential is maximal for about 30 km electric range. Compared to conventional vehicles both PHEV and BEV can significantly reduce well-to-wheel CO_2 emissions when using renewable energies for recharging. The maximal reduction potential per vehicle is larger for PHEV and achieved at smaller range than for BEV.

Keywords: Electric Vehicles, BEV, PHEV, GHG emissions, electrification potential

1 Introduction

Electric vehicles are widely seen as the propulsion technology of the future, most importantly as they have the potential to reduce green house gas (GHG) emissions from the transport sector [1]. A variety of electric vehicle types exists with different benefits. Here, we distinguish between battery electric vehicles (BEV) that run exclusively on electricity and plug-in hybrid electric vehicles (PHEV) that combine electric and conventional propulsion. While a BEV is advantageous due to its simple drive train and the absence of tailpipe emissions, the main advantages of a PHEV are an overall driving range comparable to conventional vehicles and a smaller battery compared to BEVs. The use of a small battery in a PHEV reduces emissions during the production phase of the vehicle and, in addition, reduces purchasing price (see e.g. [2]).

Altogether, although BEV and PHEV have different favoring conditions on individual level, with regard to their potential to reduce emissions of car fleets, BEV and PHEV constitute (imperfect) substitutes and the question arises which vehicle type has a higher potential to reduce

GHG emissions in a fleet, e.g. on national scale. The aim of the present paper is to analyze the potential for BEV and PHEV to electrify car fleets and to reduce GHG emissions for varying electric driving ranges.

The outline is as follows. Section 2 gives an overview on existing studies of the subject and section 3 presents the data and methodology for our analysis. Section 4 contains the results and is followed by a summary in section 5.

2 Existing studies

Studies on benefits of electric vehicles differ in their focus. The first group of studies compares different alternative vehicle designs (such as BEV or PHEV) among themselves or with conventional vehicles. The approaches rely on average parameters, usually calculated via simulation, i.e. these studies deduct a single consumption or emission value on vehicle level for the entire fleet, expressed in gCO_2/km. This value is used to compare the benefits of different drive train technologies or specifications, as e.g. the battery size [3]. This approach is especially used in life cycle analyses of advanced vehicle concepts [2,4-6], in studies analyzing emission reduction potential of electric vehicles with a focus on electricity generation or in studies assessing future prospects [7,8]. Finally, this approach is also suitable for the assessment of the technical development of new vehicle concepts [9].

A second group of studies analyses travel behavior on an individual level to determine user specific optimal drive train configurations including the analysis of financial benefits and the variation of battery size [10-13]. Some of these studies use individual driving behavior to evaluate sales potentials of the different vehicle concepts [14,15].

Finally, the present work can be sort into a third group of studies that directly compare BEV and PHEV with regard to their economic and ecologic potential on fleet level. The comparison is complex as it cannot rely on average fuel economy, especially as official test cycle fuel economy does not account for user specific differences [16]. More specific, for every user, the share of long distance trips is different and thus is the share of kilometers driven electrically [16]. In a life cycle analysis, Meinreken and Lackner [2] compare the potential of BEV and PHEV with regard to their potential to reduce GHG emission within a fleet, based on the NHTS dataset. They use a methodology that uses a relative measurement of emission reduction by new vehicle types and find the potential of especially BEV to be limited on a high level mainly due to increasing emissions during production of larger batteries. Using the same dataset, Khan and Kockelman [17] calculate the number of households adopting BEV and PHEV, respectively. Within their analysis, they find high adoption rates for BEV both in single and two car households if allowing for a certain number of days that cannot be driven with the respective BEV. In addition, PHEV with an AER above 40 miles are found to potentially electrify more than 50 % of kilometers travelled on average.

Accordingly, the present study aims at comparing BEV and PHEV with regard to their potential to reduce GHG emissions within the German passenger car fleet. We use longitudinal German travel data (see section 3 data and methods) to simulate driving with a BEV on the one hand and with a PHEV on the other hand. For everyday trips within the all electric range of the vehicles, both BEV and PHEV are propelled by the electric motor. For trips above the all electric range, the BEV has to rely on alternatives. Here we assume a conventional car as an alternative. I.e. using a BEV, long distance trips are driven completely on conventional driving mode. In contrast, a PHEV exploits its all electric range and switches into conventional mode whenever the battery is fully depleted. The share of kilometers driven electrically is usually expressed as the utility factor (UF) of a PHEV. The utility factor can be used to describe driving behavior or within a fleet or on individual level. As a result we get the share of kilometers travelled electrically for both vehicle concepts, BEV and PHEV, including a sensitivity analysis for various battery sizes. We also analyze the effect of one additional charging stop per day by assuming an increased all electric range for all users. Finally, we deduce potential CO_2 savings from electrification.

3 Data and Methods

3.1 Data

In order to study the effect of annual vehicle kilometers travelled (VKT) and other factors on the utility factor (UF) of PHEV individually we conducted a simulation of PHEV driving with mobility data of conventional vehicles. Due to the high irregularity of vehicle usage patterns, we need a reliable data basis with an observation period of several days. This requirement excludes many national household travel surveys such as the US NHTS. Here, we use the German Mobility Panel (MOP). The MOP is one of two national travel mobility surveys for monitoring everyday travel personal mobility in Germany. The survey is annually commissioned since 1994 by the German Federal Ministry of Transport and Digital Infrastructure (MOP 2010, [18]). In the annual survey about 1,000 households report their daily travel patterns over a period of one week in autumn. The survey collects data about all trips of the household members including start and end times, trip purposes, distances, and means of transportation used. Moreover, it includes socio-demographic data of households and household members are gathered.

Since MOP is a household travel survey which focuses on people and their trips, we have to assign trips to vehicles if unambiguously possible (see [14] for details). We use data from 1994 until 2010 and limit our analysis to vehicles with stated annual VKT with less than 20 % difference between the stated annual VKT and the annual VKT as extrapolated from the observed weekly VKT. This ensures that the observed driving week can be used to simulate realistic UF and reduces the sample to N = 780 vehicles with 5,140 non-zero daily travel distances. Otherwise, the behaviour from one non-representative week would be used to extrapolate to the rest of the year.[1] The mean annual VKT is 13,785 km and the median 12,000 km.

3.2 Methods and Assumptions

We simulate each driving pattern individually as PHEV and BEV with different electric driving ranges. Daily VKT longer than the electric range are excluded for BEV and the utility factor for PHEV is calculated individually. When simulating PHEV driving based on data of conventional vehicles, we assume a complete recharge every night, electric driving until the PHEV model-specific AER has been reached and conventional driving thereafter. Thus, we calculate for every user the mean UF as the ratio of distance in charge depleting mode and total distance travelled.

To take a potential availability of public charging infrastructure or a charging possibility at the workplace into account, we analyse also the effect of an additional fast charging stop by assuming a total daily electric range of 180% of the vehicle´s electric range.

For the calculation of well-to-wheel CO_2 emission savings, we use a conventional vehicle as reference with 130 gCO_2/km. Furthermore, each kilometre of electric range is assumed to be connected with 40 kg CO_2/kWh or 8.3 kg CO_2/km (for an assumed electricity consumption of 20 kWh/100km[2]). The CO_2 content from electricity generation translates to 0 gCO_2/km for renewable energies, 99 gCO_2/km for natural gas (495 gCO_2/kWh), 115 gCO_2/km for the US mix (with assumed 566 gCO_2/kWh), 167 gCO_2/km for hard coal (835 gCO_2/kWh) and 190 gCO_2/km for lignite power generation (950 gCO_2/kWh – see [16] for details). For a comparison with other major markets, we can use their average specific CO_2 emissions (see [19] for country specific emission factors): China with 766 gCO_2/kWh or 153 gCO_2/km is comparable to hard coal; France (79 gCO_2/kWh or 16 gCO_2/km), Sweden (30 gCO_2/kWh or 6 gCO_2/km) and Norway (17 gCO_2/kWh or 3 gCO_2/km) are comparable to renewable electricity generation. Germany's electricity generation has a smaller yet comparable CO_2 content as the US mix (461 gCO_2/kWh in 2010 or 92 gCO_2/km).

4 Results

4.1 Electrified fleet kilometers

Electric vehicles can electrify passenger car road transport. The overall share of annual vehicle kilometers travelled (VKT) in a large car fleet that can be electrified depends on the electric range and the availability of a range extender when the battery has been fully depleted. Fig. 1 shows simulation results for the share of total fleet kilometers that can be electrified by PHEV (blue line) and BEV (red line). For PHEV a share of each vehicle´s daily VKT can be electrified even for small ranges, whereas for BEV only those daily VKT can be electrified that are within the electric driving range. Accordingly, PHEV show an earlier growth of electrified kilometers than BEV, the latter show noteworthy fleet electrification potential only for more than 40 km of electric

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[1] Note, however, that running the simulation without this additional constraint on the data produces qualitative similar results.

[2] We take the average EPA electricity consumption from five mass market vehicles (all in kWh/100km): 23.6 for Tesla Model S, 24.9 for the Mercedes B class ED, 18.0 for VW e-Golf, 18.6 for the Nissan Leaf and 16.8for the BMW i3, resulting in 20 kWh/100 km.

driving range. Due to some vehicles showing long distance trips and since long distance trips contribute heavily to a fleets overall VKT, a 100% of electrification are very difficult to achieve and possible only at very high electric ranges (over 500 km). The difference in electrification potential between PHEV and BEV is maximal (see inset in Fig. 1) at about 30 km of range where PHEV can electrify more than 50% of the total fleet kilometers and BEV only about 17% of the fleet kilometers.

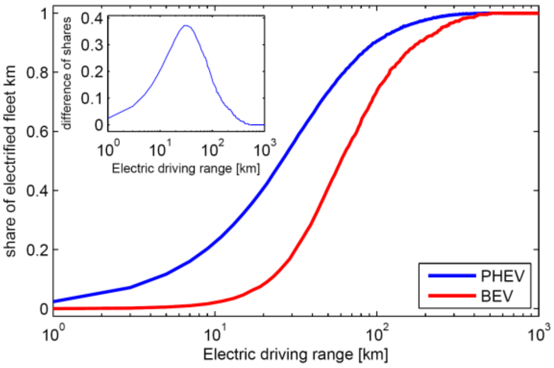

Figure1: Share of electrified fleet kilometers for different electric ranges.

The electrification potential for a whole car fleet is a result of electrification of many individual vehicles. For given range, the share of vehicle kilometers electrified can differ substantially between drivers. To demonstrate this effect, Fig. 2 shows several quantiles of the individual vehicle kilometers electrified. The median share of electrified kilometers show a similar behavior with varying electric range as the share of fleet kilometers electrified (cf. Fig. 1). However, the median of the individuals reaches 100% earlier than total fleet electrification. This is again due to drivers with very high daily and annual VKT that require high electric driving ranges and contribute noteworthy. Furthermore, Fig. 2 shows the 10% and 90% quantiles (dotted lines) as well as 25% and 75% quantiles (dashed lines) of the individual share of kilometers electrified by PHEV and BEV. We observe a wide spectrum of electrification for fixed electric driving range both for PHEV and BEV. For example, a PHEV with 30 km of range leads to range of 30 to 80% electrification (10 and 90% quantiles) and similar ranges can be observed for BEV. Accordingly, the total electrification of a fleet is a result of many individual electrifications with a broad spectrum of electric driving shares.

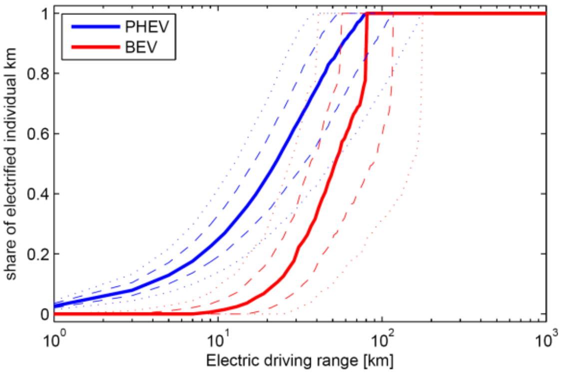

Figure2: Different quantiles of the share of electrified individual kilometers (solid: median, dashed: 0.25 and 0.75, dotted: 0.1 and 0.9 quantile).

Especially from a political point of view, the question of mileage electrification potential could be seen the other way around: how much range is needed to enable a desired share of electrified fleet kilometers? This is shown in Figure 3 (compared to Figure 1, the abscissa and the ordinate are switched).

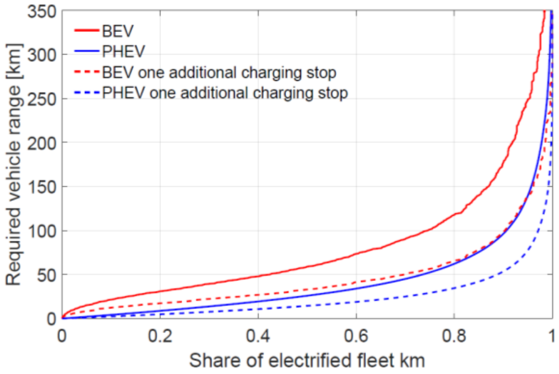

Figure3: Share of electrified fleet kilometers for different electric ranges.

Figure 3 illustrates that notably for smaller ranges, PHEV can achieve a much larger share of electrified fleet kilometers (for AER below 250 km). I.e., for a target share of 90% electrified kilometers, a PHEV would need a vehicle range of approximately 100 kilometers whereas the range of a BEV would have to be 175 kilometers. Naturally, an additional charging stop per day reduces required AER to reach a predefined share of electrified fleet kilometers (shown as dotted lines in Figure 3). However, it is especially interesting to note the good accordance of the fleet electrification potential of a PHEV (solid blue line) and the potential of a BEV with one additional charging stop per day (dotted red line). The conventional drive train makes a PHEV more expensive compared to a BEV with the same AER - for example, BMW charges ca. 4.000 € (excl.

VAT) for the range extender as additional option to the BMW i3 [20]. By arguing that these additional cost might be invested in additional (public) charging infrastructure for BEV, the comparison of a PHEV assuming only overnight charging and a BEV with an additional daily charging stop seems adequate. Similarly, an increase of the BEV´s battery capacity as another option to reach cost parity with PHEV would be possible, leading to a 50 km higher AER[3] of BEV compared to a PHEV. Against this background, the range extender of a PHEV, the set-up of (public) charging infrastructure and the increase of battery capacity can be seen as means to increase the limited electric range of EV and further research is necessary to compare these means from a technical as well as an economic point of view (for details see e.g. [22]).

In summary, PHEV allow for more electrification both for fleets and individuals at given electric driving range. This is, to some extent, a trivial consequence of partial electrification of all trip for PHEV as compared to full electrification of only some trips for BEV. Yet, the magnitude of the difference can be large, especially for realistic ranges between 20 and 150 km. However, these analyses neglect for higher vehicle weight and therefore consumption as well as higher cost for a PHEV due to the conventional drive train. While the effect of the additional consumption might be negligible for larger AER (for the BMW i3, which is available both as BEV and PHEV with the same battery capacity, EPA electricity consumption differs by approximately 10%), additional cost might be substantial raising the question of assessing the range extender as one of several options to increase daily ranges of electric vehicles.

4.2 Well-to-wheel GHG emissions

Higher electric ranges lead to higher electrification of vehicle kilometers travelled. However, the production of large batteries for high electric ranges is energy-intense and implies a trade-off in CO_2 emission savings between vehicle production and vehicle usage. We analyze this effect by comparing the WtW CO_2 savings of fleet electrification level as compared to the usage of a conventional vehicle. We calculate the CO_2 savings over a lifetime of four years from the electrification of a large car fleet by PHEV (dashed lines) and BEV (solid lines) for recharging with different electricity types in Fig. 4. The fleet CO_2 savings have been normalized by the number of vehicles to obtain the average WtW per vehicle. Shown are results for five different carbon contents of electricity generation: renewable energies (blue), natural gas (green), the US mix (red – the CO_2 content is similar to the German electricity mix), hard coal (cyan) and lignite (purple).

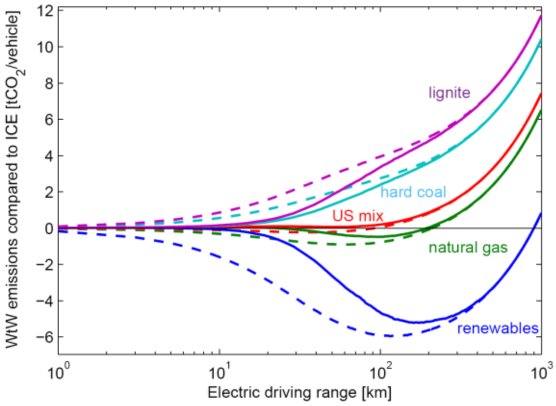

Figure4: Well-to-wheel (WtW) CO2 emissions per vehicle for PHEV (dashed) and BEV (solid) as compared to a conventional vehicle versus electric range for different electricity types (blue: renewable energies, green: natural gas, red: US mix, cyan: hard coal, purple: lignite).

Since the CO_2 savings are obtained from comparison with a conventional vehicle (130 g CO_2/km) only charging electricity from renewable energy generation (0 gCO_2/km), natural gas power plants (99 gCO_2/km) and the US mix (115 gCO_2/km) can achieve actual savings. In all other cases, the energy intense battery production and the CO_2 content of the electricity assumed for recharging leads to higher WtW emissions than for a conventional vehicle. With respect to major EV markets, the CO_2 emission factors of France, Sweden and Norway are close to renewable generation, Germany is slightly below the US mix, and China's electricity generation shows specific CO_2 emissions comparable to hard coal.

The tradeoff between longer electric range and higher CO_2 emissions from battery production leads to a maximum in fleet emission savings (or a minimum in WtW emissions) for low carbon electricity. For BEV, the highest savings of about 5.2 ton CO_2/vehicle can be achieved at a range of 175 km for renewable energies and of 0.5 ton CO_2/vehicle at a range of 95 km range for natural gas. For PHEV, a range of 115 km is optimal when

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[3] Assuming range extender cost of 4.000€, battery cost of 400€/kWh and an average electricity consumption of 0.2 kWh/km.

charging electricity from renewable sources with emission savings of about 6 ton CO_2/vehicle and about 1 ton CO_2/vehicle at 60 km range when using natural gas. Thus, PHEV can achieve higher savings at smaller ranges when assuming only one full charge every night.

In summary, high electric driving ranges come at the cost of high CO_2 emissions from vehicle production. This tradeoff leads to an optimal PHEV and BEV electric driving range in terms of WtW CO_2 emission savings. Under same infrastructure availability , the optimal range is smaller for PHEV than BEV since PHEV can electrify higher shares of fleet kilometers with the same range as BEV.

4.3 Discussion

Our results come with some uncertainty. Firstly, the fleet electrification simulation relies on several simplifying assumptions such as one full recharge over night and fixed energy consumption per km for all electric ranges. Whereas the first seems a reasonable approximation for actual user behavior, the latter seems questionable since increased range derives from larger batteries with higher vehicle mass. Thus, energy consumption should increase with electric driving range. However, the effect should be small for not too large ranges (up to 300 km) and our overall results should thus not be affected by inclusion of range dependent energy consumption.

Noteworthy CO_2 savings are achieved when EVs are charged from renewable energy sources. Yet, how to ensure or incentivize renewable electricity for EV recharging remains an open problem. Furthermore, since renewables are already contributing to CO_2 emission reductions in the energy sector, the renewable electricity for EVs should stem from *additional* renewable electricity generation. Since electricity as such cannot be labeled, bookkeeping solutions could be one way forward to this problem: annual EV sales and average annual VKT are recorded and EV sellers are then forced to purchase the same electricity from renewable sources. Thus the total renewable electricity generation grows but additional generation for EVs is ensured ex-post. However, the details of such a procedure and other options as well as its political implementation remain an open issue.

The CO_2 saving potentials depend on the assumed vehicle life time. Since vehicle battery production is carbon intense and PHEV as well as BEV usage is connected with low CO_2 emissions, the CO_2 savings grow with the lifetime assumed. Here we used four years of usage which is the average vehicle ownership time for newly purchased vehicle in Germany [14]. However, future research should provide a more comprehensive comparison of the optimal ranges and estimated CO_2 savings for different lifetimes.

5 Summary

PHEV can electrify more miles than BEV for given electric range both for an individual driver as well as the total VKT of a large car fleet. The difference in fleet electrification potential is maximal for about 30 km electric range. Compared to conventional vehicles both PHEV and BEV can significantly reduce well-to-wheel CO_2 emissions when using renewable energies for recharging. The maximal reduction potential per vehicle is larger for PHEV and achieved at smaller range than for BEV.

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Authors

Patrick Plötz received a PhD in Theoretical Physics from the University of Heidelberg. He is working as senior scientist in the Competence Center Energy Technology and Energy Systems at the Fraunhofer Institute for Systems and Innovation Research ISI. His current research focuses on energy efficiency and electric vehicles.

Simon Funke is a Research Associate at the Competence Center Energy Technology and Energy Systems at the Fraunhofer Institute for Systems and Innovations research. He studied industrial engineering at the Karlsruhe Institute of Technology, Germany, and Universidad de València, Spain. Areas of interest: renewable energies and automotive technology, special interest in alternative drive systems.