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Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types

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HIGHLIGHTS

- Optimization of the battery size of PHEVs and EREVs under German market conditions.
- Focus on heterogeneity across drivers (e.g. mileage, trip distribution, speed).
- Optimal battery size strongly depends on the driving profile and energy prices.
- OEMs require a modular design for their batteries to meet individual requirements.

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ABSTRACT

There are ambitious greenhouse gas emission (GHG) targets for the manufacturers of light duty vehicles. To reduce the GHG emissions, plug-in hybrid electric vehicle (PHEV) and extended range electric vehicle (EREV) are promising powertrain technologies. However, the battery is still a very critical component due to the high production cost and heavy weight. This paper introduces a holistic approach for the optimization of the battery size of PHEVs and EREVs under German market conditions. The assessment focuses on the heterogeneity across drivers, by analyzing the impact of different driving profiles on the optimal battery setup from total cost of ownership (*TCO*) perspective.

The results show that the battery size has a significant effect on the *TCO*. For an average German driver (15,000 km/a), battery capacities of 4 kWh (PHEV) and 6 kWh (EREV) would be cost optimal by 2020. However, these values vary strongly with the driving profile of the user. Moreover, the optimal battery size is also affected by external factors, e.g. electricity and fuel prices or battery production cost. Therefore, car manufacturers should develop a modular design for their batteries, which allows adapting the storage capacity to meet the individual customer requirements instead of "one size fits all".

1. Introduction

The reduction of greenhouse gas emissions (GHG) and petroleum consumption is the major challenge for the transport sector in the 21th century. Transport is responsible for about 20% of total GHG emissions in the EU in 2011 (EEA, 2013). The European Commission aims to cut 60% of CO_2 emissions by 2050 with regard to the 1990 level (European Commission, 2011). In this context, the manufacturers of light duty vehicles, which are responsible for 75% of total transport GHG emissions (EC, 2012), are required to decrease average CO_2 emissions of new passenger cars to 95 g/km by 2020. However, the new regulation includes a phase-in period, which allows OEMs to meet this target with only 95% of their car fleet in 2020. Starting in 2021, 100% of the relevant fleet has to fulfill 95 g/km limit. Even more ambitious regulations (68–78 g/km) are currently discussed for the following period 2020–2025 (European Parliament, 2013). Achieving these targets will not be feasible with conventional internal combustion engines. One of the most promising powertrain technologies are plug-in hybrid electric vehicle (PHEV) and extended range electric vehicles (EREV) (Shiau et al., 2009, Peterson et al., 2011, Özdemir and Hartmann, 2012, Bandivadekar et al., 2008). They combine local emission free driving of battery electric vehicles with the unrestricted driving range of conventional cars powered by gasoline or diesel (Peterson, Michalek, 2013). However, the battery is still a very critical component due to the high production cost and heavy weight (Shiau et al., 2009, Özdemir and Hartmann, 2012, Bandivadekar et al., 2008, Peterson, Michalek, 2013, Shiau et al., 2010, Shiau, 2011). Therefore, the right sizing of the battery is the key for electric powertrains to meet customer expectations and become cost competitive against

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conventional technologies. There are several recent studies that focus on the optimal battery size for grid connected hybrid electric vehicle for the US market (Shiau et al., 2009, Peterson, Michalek, 2013, Shiau et al., 2010, Shiau, 2011, Wu et al., 2011), and for the European market (Özdemir and Hartmann, 2012, Ernst et al., 2011, Plötz et al., 2012).

Among the US studies, Shiau et al. (2009, 2010) compared several PHEVs with different electric driving ranges with regard to the economic and environmental feasibility for an average US driver. In their analyses, best suitable battery size is determined for different targets such as minimum net life cycle cost, and minimum GHG emissions. The results show that the optimum battery size is significantly lower for minimum cost target than for minimum GHG emissions target for a specific driver type. Furthermore, Shiau and Michalek (2011) analyzed the effect of different average daily driven distances. The results show that a switch from conventional vehicle to a PHEV reduces the life cycle GHG emissions significantly. Economic implications are not covered in this work. Peterson and Michalek, (2013) investigated the net life cycle air emissions from PHEVs for different battery sizes and charging strategies for an average US driver. The results show that emissions of CO_2, SO_2 and NO*x* can be reduced with increasing battery size. Wu et al. (2011) analyzed the component sizing of plug-in vehicles with the aim to optimize the powertrain costs under different cycles. However, in this study only the production costs of the powertrain are considered. The optimization did not include running costs (such as gasoline or electricity from the grid), which does not represent total cost of ownership (*TCO*).

Besides the studies for the US market, there are also studies that concentrated on the European (especially German) market. Özdemir and Hartmann (2012) analyzed the energy consumption of PHEVs (for grid electricity and fuel), costs and GHG abatement costs depending on the electric driving range for an average driver under the assumed German market conditions in 2030. The results show that the optimum electric driving range for minimum costs and for minimum GHG abatement costs are between 12–32 km, and between 16–23 km, respectively. Furthermore, they also investigated the effect of changing oil price, annual mileage, battery costs, energy consumption and interest rate. Main factors that influence the results are identified as annual mileage and oil price. Ernst et al. (2011) investigated similarly the economic implications and CO_2 emissions of PHEVs with different battery sizes for an average German driver under the assumed market conditions in 2020. The results show that PHEVs are cost competitive, if the battery size is small (e.g. 4 kWh). Furthermore, the recharging strategies are not found to be significant for the cost calculation results. Plötz et al. (2012) focused on the analytical solution of the *TCO* minimization problem for PHEV drivers with respect to the battery size. The results show that the optimal battery size is about 10 kWh (50 km electric driving range) for battery costs of 200 EUR/kWh for the average German driver.

Although the impact of PHEV battery size on costs and GHG emissions has already been studied in the literature in some detail, existing studies neglect some significant aspects in this context. Firstly, they do not account for the heterogeneity which can be observed across different driver types. The papers discussed before typically assume a constant driving distance (Shiau et al., 2009) or a trip distribution based on an average driver (Özdemir and Hartmann, 2012, Plötz et al., 2012, Ernst et al., 2011). However, in reality, the daily driving distance varies significantly during one year and across different user types (DLR & Infas, 2010). Secondly, previous studies do not consider that drivers with higher annual mileage typically spend more time on motorways with a higher average velocity than that by drivers with lower annual mileage, which in consequence effects the energy consumption and the share of electric driving of the PHEV. In this context, Ernst et al. (2011) identifies different driving profiles for PHEVs as a future research area. Thirdly, none of the existing studies considered the technical differentiation between hybrid architectures such as parallel (PHEV, plug-in hybrid electric vehicle) and serial (EREV, extended range electric vehicle) powertrain configurations. Lastly, batteries are subject to degradation and aging processes which require a substantial oversizing of the initial energy capacity, which is not taken into account by some studies (e.g. Plötz et al., 2012).

Therefore, this paper aims to close these gaps by introducing a holistic approach for the optimization of the battery size of PHEVs and EREVs under German market conditions by considering the battery degradation and secondary effects of additional mass on the energy consumption. The assessment puts special focus on the heterogeneity across drivers, by analyzing the impact of different driving profiles on the optimal battery setup from total cost of ownership perspective for the year 2020 in Germany. Furthermore, specific CO_2 emissions (tank to wheel – TTW and well to wheel – WTW) for grid connected cars are analyzed as a function of battery size. The most relevant data for this analysis, e.g. energy consumption or battery costs, is based on own vehicle simulations and detailed cost models.

In the following, Section 2 introduces the methodology to identify a cost optimal design for the battery capacity of grid connected vehicles. Section 3 describes the underlying total cost of ownership model and the empirical data used to characterize the driving behavior. The model is applied to the situation of different driver types and the resulting implications on energy consumption, mobility cost and GHG emissions are discussed (Section 4). The sensitivity of the results with regard to changes in the underlying input parameters is analyzed to understand the dependences from external factors, e.g. energy prices. Finally, Section 5 summarizes the policy implications and gives an outlook on future research questions.

2. Methodology

The sizing of the battery has multiple implications on the technical properties and the financials of hybrid electric cars (see Fig. 1). The installed battery capacity directly affects the curb weight and the energy consumption of the car, which in combination determine the all-electric driving range. Besides the technical configuration of the powertrain, the share of electric driving is also influenced by the driving behavior of the user. In general, a larger battery capacity leads to a higher share of electric driving because more trips can be covered within the electric driving range of the car. As electric motors offer significantly better energy efficiency than internal combustion engines (ICE) a higher share of electric driving causes lower operating costs for the car holder and lower CO_2 emissions. On the other hand, the production cost of the battery and the associated purchase price for the custumer increase with rising energy storage capacity. Consequently, the optimal battery size from the perspective of a car buyer is a tradeoff between one time investment costs and running costs over lifetime. To identify the minimal cost car configuration, the *TCO* are used in the following to evaluate the overall cost efficiency. Thus, the objective function of this optimization problem can be expressed as:

$$\min TCO = f(E_{Bat}, Y_n(D_n), Z) \quad (1)$$

where E_{Bat} equals the total nominal battery capacity in kWh (including the oversizing due to degradation). The variable Y describes the individual driving behavior of the user n. The distributions of the daily trip lengths as well as the average driving speed are modeled as a function of the annual mileage D_n.