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Battery sizing for serial plug-in hybrid electric vehicles: A model-based economic analysis for Germany

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ABSTRACT

The battery size of a Plug-in Hybrid Electric Vehicle (PHEV) is decisive for the electrical range of the vehicle and crucial for the cost-effectiveness of this particular vehicle concept. Based on the energy consumption of a conventional reference car and a PHEV, we introduce a comprehensive total cost of ownership model for the average car user in Germany for both vehicle types. The model takes into account the purchase price, fixed annual costs and variable operating costs. The amortization time of a PHEV also depends on the recharging strategy (once a day, once a night, after each trip), the battery size, and the battery costs. We find that PHEVs with a 4 kWh battery and at current lithium-ion battery prices reach the break-even point after about 6 years (5 years when using the lower night-time electricity tariffs). With higher battery capacities the amortization time becomes significantly longer. Even for the small battery size and assuming the EU-15 electricity mix, a PHEV is found to emit only around 60% of the CO_2 emissions of a comparable conventional car. Thus, with the PHEV concept a cost-effective introduction of electric mobility and reduction of greenhouse gas emissions per vehicle can be reached.

1. Introduction

Anthropogenic CO_2 emissions contribute to climate change and may cause substantial societal costs in the future (Stern, 2006) if significant and rapid CO_2 mitigation is not achieved. Anthropogenic CO_2 emissions originate mainly from the combustion of fossil fuels. Due to their very intensive use of fossil fuels the power generation and transportation sectors play a major role in the CO_2 abatement strategies in Europe in general and in the largest European economy, Germany, in particular. These sectors contributed 40.8% and 17.7%, respectively, to overall anthropogenic CO_2 emissions in Germany in 2008 (UBA, 2010). Therefore, the European Commission and the German government have adopted several CO_2 reduction policies in various energy-related fields. For example, the transport sector will be regulated via emissions performance standards for new passenger cars. Between 2012 and 2015, the average CO_2 fleet emissions of a certain percentage of an automaker's annual new passenger car sales must not exceed 130 g CO_2/km, with gradually stiffened interim targets. By 2020, the target value for the fleet emissions is 95 g CO_2/km. The regulation also defines 'super-credits' for cars with emissions below 50 g CO_2/km, allowing them to be counted as 3.5 cars in 2012. These 'super-credits' will be gradually phased-out until 2016, but until then might act as a significant incentive for car manufacturers to accelerate the diffusion of PHEVs (EU, 2009), as their tailpipe CO_2 emissions are reduced to zero in electric driving mode. Beyond that, the German government has set the further-reaching goal to get one million electric vehicles on Germany's roads by 2020 (Bundesregierung, 2009), because electric mobility can offer manifold benefits (Sovacool and Hirsh, 2009), such as the reduction of CO_2 emissions by means of reducing oil-based fuel consumption in the transport sector and by increasing electricity generation from volatile renewable energy sources, using electric vehicles as active storage systems in the grid—the so-called vehicle-to-grid (V2G) concept (Kempton and Tomic, 2005a, 2005b). With this in mind PHEVs offer the possibility to reap the benefits of electric mobility by simultaneously overcoming its major barriers on the consumer side, because they enable motorists to drive in electric mode during parts of their trips, without having the limitations concerning the driving range of full-electric cars.

However, a transition to electric car mobility strongly depends on consumer acceptance, which in turn is heavily affected by the cost-effectiveness, the driving range and the recharging conditions

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for these new types of cars, especially when they are compared to conventional vehicles with an internal combustion engine (ICE) (Dena, 2010; Achtnicht et al., 2008). Since the PHEVs' electric drivetrain is an additional cost factor it is necessary to have a closer look at the total cost of ownership (TCO) over the vehicles' lifetimes, which primarily consists of operating cost, maintenance cost and purchase price, to assess their economic effectiveness. The purchase price of PHEVs in turn is mainly influenced by the battery cost and thus by the car's battery size, which differs largely among the recently announced PHEVs, depending on the manufacturer. For instance, while the Toyota Prius will be endowed with a 5.2 kWh battery and is designed as a parallel hybrid concept, the Chevrolet Volt and Volvo Recharge will be equipped with much larger 16 kWh batteries and a serial hybrid concept, although all these PHEVs will on average have the same engine power of 100 kW. Moreover, not only the purchase price is affected by the electrification of the drivetrain, due to, e.g. the downsizing of the ICE and the additional need for an electric engine and power electronics, but also the operating and maintenance costs are reduced. This is caused by a general decrease in fuel consumption, considerably lower fuel costs when driving pure electrically, and possibly lower motor vehicle taxes compared to conventional ICE vehicles, if the vehicle's taxable base also accounts for CO_2 emissions and not solely for engine displacement, as is currently the case in Germany (BMF, 2009).

The disparity in these three cost segments between PHEVs and conventional ICE vehicles expectedly results in a cost advantage of the PHEV when the battery costs are ignored in the calculation. This value can be contrasted with different battery sizes and battery price scenarios to calculate the most favorable battery size regarding cost-effectiveness.

In this paper we investigate the economic consequences of different battery sizes of an average PHEV in Germany and undertake a sensitivity analysis with respect to key parameters. The second aim of the paper is the calculation of the annual CO_2 emissions of the two different power trains under various energy mix scenarios, because aside from economic factors environmental considerations are a main decision criterion in vehicle choice in Germany (Dena, 2010).

The remainder of this paper is organized as follows: the methodological approach is outlined in more detail in Section 2. In Section 3 the energy consumption of the gasoline engine, the electric drivetrain and the range extender (RE) are calculated and compared. Section 4 assesses the total cost of ownership. For this purpose, we estimate the development of the gasoline and electricity prices, calculate the mobility costs for an average driver, derive the cost differences regarding initial and annual costs up to 2020, and conduct a sensitivity analysis to assess the impact of changes in the technical and economic assumptions. In Section 5, the CO_2 emissions of the vehicles are estimated for different fuel mix and vehicle charging scenarios. Section 6 summarizes and concludes.

2. Methodological approach

Lifecycle costs of PHEVs have been assessed in the past (Biere et al., 2009; Hackbarth et al., 2009; Shiau et al., 2009; Silva et al., 2009; Simpson, 2006; Sioshansi et al., 2010; Van Vliet et al., 2010; Werber et al., 2009) by using various approaches regarding (1) the bandwidth of vehicles covered concerning their all-electric range, drive train design, and annual mileage; (2) the level of detail of the energy consumption calculation for the different drive trains and vehicles; and (3) the countries considered, such as the US, Japan, the Netherlands or Germany, and framework conditions (e.g. regarding energy prices and taxes). In this study, we decided to keep the cost-effectiveness analysis narrow but very detailed and realistic because such a detailed energy consumption model, to the best of our knowledge, has not been applied to the case of Germany before. Thus, we adopted the following approach and assumptions: to contrast the costs of an average conventional ICE compact car with an engine power of about 100 kW with a comparable PHEV, both used by the average German car driver over a 10-year period, varying the battery size. As only the serial hybrid drive train offers the possibility and modularity to connect batteries of different capacity (here: 4–20 kWh) to the drive train, it will be the base for the analysis in this study. Furthermore, most of the pre-announced PHEVs that will be available in the near future (including two out of three vehicles mentioned in the previous section) are based on this concept. Additionally, we compare the PHEV with an optimized ICE vehicle with less power, since ecologically concerned customers might also take such an option into consideration (Dena, 2010).

The focus of our calculations lies on Germany regarding the vehicle taxes, the projected development of energy prices until 2020, and the driving pattern of the average German user of a gasoline-fueled vehicle, the latter of which is derived from a large field study (BMVBS, 2004).[1] The driving pattern of the average user of a gasoline-fueled car is chosen for assessing the potential of PHEVs to replace the average conventional car, because in Germany 79% of the privately owned vehicles run on gasoline and are driven approximately 12,000 km per year (Destatis, 2011). For such a low annual mileage a typical diesel-fueled vehicle would not be economical. In addition, the average driving patterns of owners of diesel-fueled cars show a larger share of long-distance highway trips, where the advantages of electric drivetrains are minimal and, accordingly, PHEVs are less competitive. For these reasons diesel-fueled cars are not considered in the following.

As mentioned above, the TCO over a vehicle's lifetime can be split up into three parts—purchase price, fixed annual costs and operating costs. First, we determine the differences in the initial or vehicle purchase costs of a PHEV compared to a conventional ICE vehicle based on data from the literature (Biere et al., 2009; IES, 2008; Graham, 2001; Metric Mind Corporation, 2009; Volkswagen, 2009; Weiss et al., 2000). The initial costs are affected by savings from the downsizing of the conventional drive train and the costs for the new electric components. The savings earned by the downsizing include savings for the combustion engine itself, derived from simplified arrangements, e.g. concerning the number of cylinders, valves, and controllers. Moreover, downsizing in this case means modifications of the drive train with the elimination of the classic gearbox and a reduction of the fuel tank volume. In contrast to a conventional ICE vehicle, the PHEV needs new components, such as the electric engine, power electronics and the traction battery, which can be expected to increase both the purchase price and the weight of the vehicle.

Second, we analyze the fixed annual costs, consisting of taxes, wear of brakes,[2] maintenance and insurance cost for the PHEV and the conventional ICE vehicle based on data from the literature (BMF, 2009), own calculations and expert interviews. Wear of brakes and vehicle maintenance cost will be lower for PHEVs due

[1] In 2010, after we had finished our calculations, an update of the 2004 mobility study was released, based on field data from 2008 (BMVBS, 2010). In terms of the vehicle use the 2010 study shows only incremental changes compared to its predecessor, in all relevant parameters. Important input data for our calculations, such as the individual trip length distribution, is still valid, including, for example, that still 80% of the daily routes are shorter than 60 km.

[2] Note that, strictly speaking, wear costs are variable and not fixed. However, due to the fact that our calculations are based on the average German car driver, characterized by a constant amount of annually traveled kilometers and a constant distribution of the trip lengths over the time period studied, the wear costs remain constant as well, and thus can be regarded as being fixed.