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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 pure 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 as well as 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 six years (five years when using the lower night-time electricity tariffs). With higher battery capacities the amortization time becomes significantly longer. Even with 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.

Key words: PHEV, e-mobility, total cost of ownership

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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, 2009b), 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 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 bigger 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 cost 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 our 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 ten-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 to 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 (incl. 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 gasoline-fueled vehicles, the latter of which is derived from a large field study (BMVBS, 2004[1]). The driving pattern of the average user of gasoline-fueled cars 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 vehi-

[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, meaning, for example, that still 80% of the daily routes are shorter than 60 km.

cle, 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 to the possibility to recuperate energy when braking and the smaller size of the ICE. Since this in turn will also lead to lower CO_2 emissions, the vehicle taxes can be expected to be lower for PHEVs. We assume that the insurance cost are constant for both types of vehicles, as they may be influenced by a number of factors for which reliable market data are not yet available. The impact on annual costs originating from a usage of the PHEV battery in a V2G system is also disregarded in our analysis, as the time horizon for the calculations is 2020, which makes significant earnings from grid services rather unlikely, at least for the case of Germany. Reasons for this are (1) the lack of the necessary infrastructure for a smart grid, and (2) prequalification guidelines for the supply of ancillary grid services, which stipulate a time availability of 95-100% and a volume of several megawatts, and, thus, would require a major market penetration of PHEVs.

Third, we calculate the most influencing factor on the total cost of ownership, the operating costs, which are derived by combining an energy consumption model with the corresponding energy prices until 2020. Energy consumption differs significantly for inner-city, rural or highway trips for PHEVs and ICE vehicles alike. Additionally, it depends on the recharge strategy/possibilities of the driver, e.g. depending on whether the battery can be recharged after each trip or not. Thus, realistic trip route and length distributions derived from the survey “Mobilität in Deutschland” (BMVBS, 2004) and realistic driving profiles, like the “Hybrid Technology Approaching Efficient Zero

[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.

Emission Mobility” (HYZEM) driving cycle as a stylized reference for real driving behavior (André, 1999), form the basis for our energy consumption calculations for each drive train, or more precisely, for the ICE mode, the all-electric mode, and the range extender mode of driving.

Besides the TCO analysis, we also assess the well-to-wheel CO_2 emissions of both the PHEV considered and the conventional ICE vehicle, by multiplying the energy consumption with corresponding CO_2 values, taking various electricity mixes into account, but without differentiating for the time-of-day of the recharge process and its impact on the electricity generation portfolio.

3 Energy consumption model

The energy consumption model combines the typical driving profile of an average German driver with the HYZEM driving cycle, and takes the different kinds of drive trains and their energy efficiencies into account. The HYZEM cycle was chosen as it is based on measured driving behavior, so that simulations result in more realistic values compared to simulations based on synthetically generated profiles, such as the New European Driving Cycle (NEDC), on which the mandatory vehicle fuel consumption calculations are based in Europe (EU, 1993).

The HYZEM driving cycle divides a distance of 60.9 km into an urban-, rural- and highway subcycle. The urban section of the driving cycle is 3.5 km long and, due to the mapped stop-and-go traffic, takes approximately 9 minutes. The top speed does not exceed 60 km/h. In contrast to that, the speed of the 11.2 km rural part fluctuates between 50 and 100 km/h, while the top speed of the highway subcycle with a length of 46.2 km goes up to 130 km/h (André, 1999).

The driving profile of the average German car user reveals that some 80% of the individual trips do not exceed 18 km, and that 80% of the daily routes do not exceed about 60 km (BMVBS, 2004). Thus, with a battery that allows for an electric driving range of 60 km the majority of all daily trips can be covered.

For simplicity reasons, we assume that every trip starts and ends with an urban driving cycle. This is slightly advantageous for the electric drive train due to its efficiency in urban driving cycles. Additionally, we deduct three battery charging strategies from the typical driving profile for the electric drive train: (1) a once-a-day charging strategy with day-time electricity tariffs; (2) a once-a-day charging strategy with night-time electricity tariffs and, (3) by assuming a high density of recharging infrastructure, the possibility to recharge the PHEV after every trip at day-time electricity prices.

3.1 Gasoline engine

The calculation of the fuel consumption of a gasoline engine is performed in several steps with a dynamic computation model. Initially, the driving resistance for every speed level of the considered average compact class car is calculated. The engine operating points can be determined based on the power requirements.

With the driving resistance and the calculation of several consumption data it is then possible to derive fuel consumption per distance as a function of the speed for each gear. The computational model is completed by assumptions concerning the fuel consumption during no-load phases (e.g. red light stops). Based on calculations for different engine operating points, for each gear and level of speed, the corresponding energy consumption can be determined. Before we adapted this approach to the HYZEM cycle, we computed the gasoline consumption of our reference vehicle based on the NEDC cycle and compared it to its official consumption data, which mandatorily has to be specified by the OEMs, to ensure the accuracy and comparability of our calculation. The consumption of the gasoline engine for the reference vehicle with a power of 100 kW turns out to be 11.6 l/100 km in the urban part, 8.4 l/100 km in the rural part, and 7.0 l/100 km in the highway part of the HYZEM cycle.

3.2 Electric power train of a serial hybrid electric vehicle

The drive train of a serial hybrid car corresponds to a drive train of an electric car with a generator powered by an ICE. There is no fixed mechanical drive-through axle to the wheels. Because of this technical feature the ICE can be run on the point of highest efficiency.

The efficiency of the entire electrical drive train is defined by the efficiencies of each component and the auxiliary consumers. The assumed degrees of efficiency have been derived from expert interviews and are depicted in Figure 1. Because of the optimization of each power train component for the drive mode the components have different efficiencies in the recuperation mode. For the power consumption of the auxiliary devices, such as air conditioning, electric power steering and braking support, assumptions were made based on experience. Specifically, we assume an average auxiliary power consumption of 5.2 kW with a utilization of 5%, since our calculations are based on an all-year-usage of the vehicles in Germany, where hot or cold weather conditions do not prevail over longer periods that require higher power consumptions. However, under extreme circumstances, such as hot summer temperatures, traffic jams or very low temperatures in winter, auxiliary devices – especially air conditioning units – may significantly influence peak energy consumption of the vehicles (Farrington and Rugh, 2000) and, accordingly, also increase the all-year average energy consumption, even though to a much lesser extent. The impact of doubling the auxiliary power consumption on the cost savings is discussed in the sensitivity analysis in section 4.6.

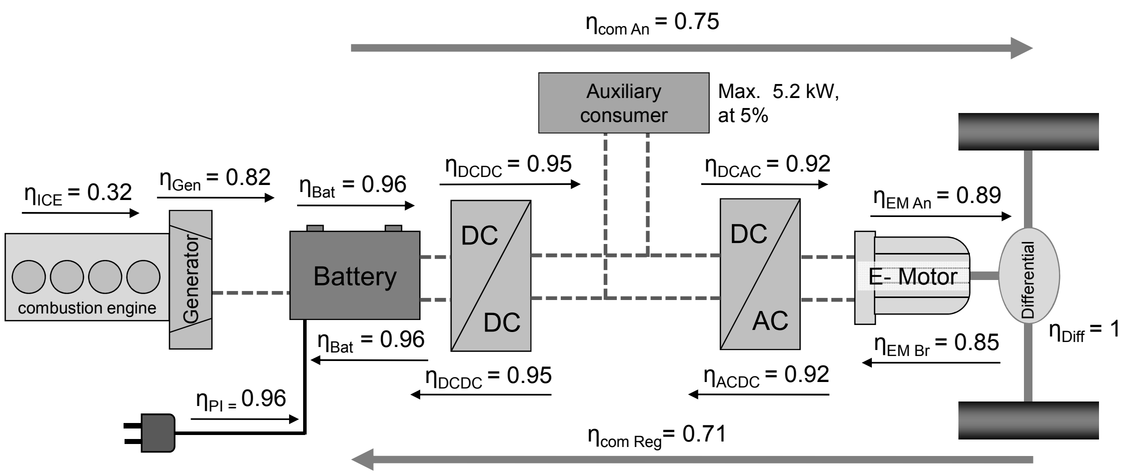

Figure 1. Component efficiencies in a serial hybrid drive train

For the whole electrical part of the power train of the serial hybrid car an efficiency of about 75% was calculated. For the recuperation mode the degree of efficiency can be determined to be 71%. This means that 53% of the energy coming from the battery can be restored in the battery during braking and, therefore, can be reused to accelerate the car after braking.

A sensitivity analysis (reported in section 4.6 below) shows the influence of different assumptions on the degrees of efficiency of the various components and the consumption of the auxiliary devices on total efficiency.

The hybrid serial drive train with standard auxiliary devices has been simulated in the HYZEM cycle. The simulations also took changes in the mass of the car due to different battery sizes into account. The following exemplary calculations are based on a compact class car with a mass of approximately 1400 kg including a 12 kWh battery. This leads to an average energy consumption of 15.4 kWh/100 km in the urban subcycle, 17.4 kWh/100 km in the rural subcycle, and 21.8 kWh/100 km on the highway.

3.3 Range extender

The range extender serves to enlarge the driving range of an electric car and is a standard part within the serial hybrid drive train concept. The battery usage strategy for this mode starts with a maximum state of charge of about 90% and decreases continuously to about 30% during the pure-electric drive. This type of operation is referred to as charge-depleting (CD) mode. With the state of charge (SoC) at 30% the vehicle switches to the range-extending or charge-sustaining (CS) mode. At this point, the ICE starts to charge the battery to a SoC of typically 35% and then switches off. When the SoC of the battery drops to 25% the engine starts again, so that the SoC is kept continuously in the interval between 25 and 35%. The engine works at continuous power at maximum efficiency. At the end of the day or the trip, respectively, the battery is connected to the electric grid and charged to a SoC of 90%, in order to avoid very high states of charge and thus a significant reduction in lifetime. This means that only about 65% of the battery’s capacity is actually used, in order to ensure that the car lifetime requirements in the automotive industry of more than 10 years are met also for the battery.

Based on the computational model the average power output for the battery with each charging strategy is deduced. The analysis of the engine map for the specific consumption leads to the point of highest efficiency with a specific fuel consumption of

212 g/kWh. The power output of about 15 kW is high enough to meet the average consumption in the urban and rural demand area, with 3.3 and 8.3 kW, respectively. During this time the surplus energy can be used to charge the battery. The usage of the combustion engine in this very efficient point leads to an energy consumption of 3.9 and 4.4 l/100 km for the urban and the rural subcycle, respectively. During the urban and rural cycle the combustion engine switches on and off to keep the SoC between 25 and 35%.

The average demand on the highway equals 22 kW so that the engine operation point needs to be adapted. The specific fuel consumption will ascend to 220 g/kWh. As a consequence, fuel consumption of the engine rises to at least 5.0 l/100 km. In this operating point the combustion engine runs permanently in order to sustain the SoC of the battery.

3.4 Comparison of the energy consumption

The conventional drive train, again based on the HYZEM simulation, consumes gasoline between 11.0 l/100 km in the rural cycle and 7.0 l/100 km in the highway cycle. The gasoline engine reaches higher efficiency levels for the case of increasing driving resistance, which leads to a reduced fuel consumption during the highway cycle.

In contrast to the conventional drivetrain, the effective energy consumption of the hybrid drive train increases with the driving resistance. Especially urban trips are by far more efficient, as only one third of the energy is used compared to highway driving. Also, it is possible to reduce the total energy consumption of the PHEVs on the highway parts, because of their aerodynamic and lightweight optimization.

The electricity consumption of the all-electrified drive train lies between 16 and 22 kWh during the different conditions of the HYZEM simulation and increases with the driving resistance. The fuel and electricity consumption of the different drive trains are shown in Figure 2.

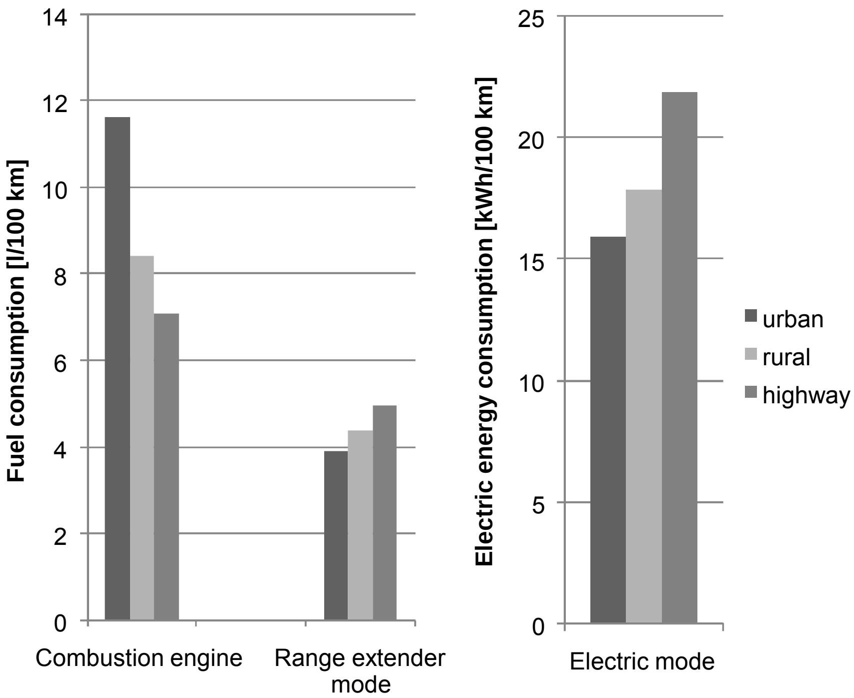

Figure 2. Fuel and electricity consumption of the individual drive trains

4 The TCO model

The development of a TCO model is highly influenced by the market prices of gasoline and electricity, since in combination with the individual energy consumption they lead to mobility costs that comprise the biggest part of the vehicle costs in addition to the initial purchase price. Further, annual costs of maintenance, taxes and wear of brakes complete the TCO assessment. In the following, we discuss these cost components in turn.

4.1 Energy prices outlook until 2020

Over the last few years, the average end-user prices of gasoline and electricity have increased continuously, a trend that was accompanied by high temporary fluctuations. Thus, projections of future prices are burdened with uncertainty and might have a relatively short validity. For our analysis we estimated the development of the electricity and gasoline prices until 2020 on the basis of historical end-user price data (BMWi, 2009)[3], which resulted in different price scenarios due to different assumptions concerning the trend function. We chose this approach to obtain disaggregated estimates of annual energy prices.

Since the gasoline price rose over the last ten years with a constant growth rate, an exponential trend line fits the price development in good compliance with the real trend, which would lead to a gasoline price of more than € 2.30/l in 2020. However, we decided to choose a more conservative linear extrapolation with a lower growth rate, which leads to a price escalation from € 1.37/l in 2010 to € 1.84/l in 2020. This trend complies with the gasoline prices for the Austrian market projected in Weyerstrass and Jaenicke (2009), that are based on the "World Energy Outlook" crude oil price projections, if they are adjusted for the higher German tax rates. The influence of more quickly escalating gasoline prices on the PHEV's economic viability is assessed in the sensitivity analysis presented in section 4.6 below.

The price of electricity in Germany developed almost linearly since 2002 (BMWi, 2009). Therefore, we decided to extrapolate the electricity price with a linear trend into the future. Furthermore, we assumed that with the increasing diffusion of smart meters in Germany, consumers will be able to recharge their PHEVs at different tariffs depending on the time-of-the-day. However, in light of the lack of a "smart grid" infrastructure in Germany mentioned above, we did not take real-time tariffs into account but assumed only two different tariffs: a day-time and a night-time tariff. We further assumed that the night-time prices of electricity will constantly lie about 30% below the day-time prices.

[3] Our end-user price estimations are only partially verified by more recent data (BMWi, 2011) and thus indicate the uncertainty in energy price projections, While the average gasoline price of € 1.41 per liter in 2010 that we assumed in the linear trend scenario matches well with the actual price of € 1.42/l, the price development in the first three months of 2011 points to a better fit of our exponentially estimated price of € 1.54/l for that year. The electricity price, however, even increased faster than we assumed in our high price scenario and, accordingly, much faster than in the major reference studies for Germany (BMU, 2008; EU, 2007; EWI and EEFA, 2008; Prognos, 2007). In 2010 the average electricity price was already at a level that we assumed to be reached not until 2013. Additionally, price data for the first three months of 2011 indicate a price development that we projected to occur by the end of 2013 (€ 0.25/kWh).

Prices of € 0.22/kWh for day-time and € 0.15/kWh for night-time electricity will then increase to € 0.31/kWh and € 0.22/kWh in 2020, respectively. Thus, the projected value of the day-time price of electricity is slightly higher than in the major reference studies (BMU, 2008; EU, 2007; EWI and EEFA, 2008; Prognos, 2007), which reflects again the conservative approach adopted in our study, as higher electricity prices clearly penalize PHEVs. The influence of more slowly increasing electricity prices on the cost-effectivenes of PHEVs is also assessed in the sensitivity analysis (section 4.6). However, such a slow rise in the electricity price in the near future seems very unlikely, unless politically backed and therefore subsidized (at least for mobility purposes), because (1) the recent price development suggests the opposite; and (2) the planned nuclear phase-out in Germany by 2022 might even sharpen this trend.

4.2 Variable mobility costs

The variable mobility costs per 100 km for the different drive trains are derived by multiplying their annual energy consumption with the corresponding price levels for the year under consideration. The result for 2011 is shown exemplarily in Figure 3.

For the combustion engine, the mobility costs decrease with increasing average speed of the subcycle. Starting with around € 16/100 km for inner city traffic, the costs decrease by 30% to about € 9/100 km for driving on the highway. The combustion engine reaches the efficient operating point very rarely in the urban part of driving, so that fuel consumption is very high.

In contrast, the costs of a hybrid vehicle in the range extender mode increase with the power demand of the trip. Through the very low energy demand in the urban cycle the mobility costs can be reduced to about € 5/100 km, which is just a third of the running costs of the conventional, non-optimized vehicle. These advantages arise especially from operating the combustion engine continuously in ranges of low specific fuel consumption.

For the all-electric driven vehicle the same argument holds true. In addition to that the lower price of the energy from the electricity grid leads to further cost advantages compared to the serial hybrid drive train. In comparison to the conventional drive train, the urban mobility costs of the electric mode are reduced to one fifth, but do not differ significantly from the range extender mode.

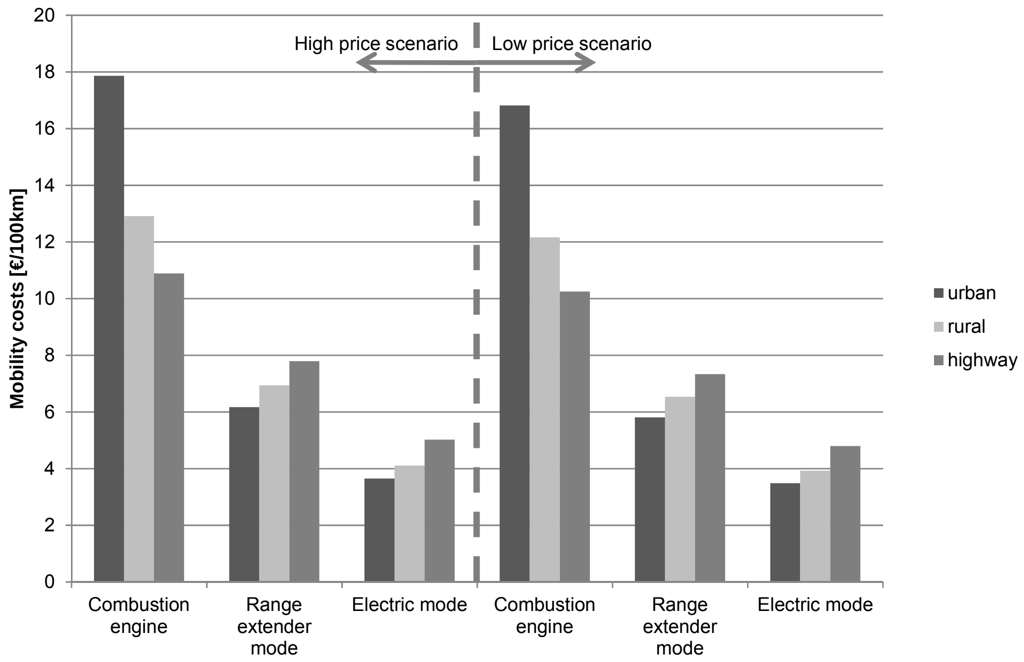

Figure 3. Mobility costs assumed for the individual drive trains in 2011

4.3 Initial and annual costs

Besides the operating costs the TCO are further composed of initial costs (essentially the purchase price of the PHEV) and fixed annual costs, the latter of which are mainly influenced by annual maintenance costs and vehicle taxes. The differences in the initial costs of a PHEV compared to a conventional ICE vehicle are based on average values from the literature[4] (Biere et al., 2009; IES, 2008; Graham, 2001; Metric Mind Corporation, 2009; Volkswagen, 2009; Weiss et al., 2000), since PHEVs will be commercially available in Germany no earlier than at the end of 2011, so that market data does not exist today – apart from the fact that even when PHEVs are available on the market

[4] The price projections have not changed significantly over the last two years, as mass production of PHEVs and electric vehicles is only emerging and thus the production volumes of power electronics for electric mobility purposes are still very small so that major new insights are unlikely.

(such as e.g. the Chevrolet Volt in the US) it will be far from trivial to calculate the incremental costs of the additional electric components.

The purchase price differences between the PHEV and the ICE vehicle occur due to two opposing effects: savings because of ICE downsizing and additional costs for the new electronic components. In our study, downsizing denotes a modification of the combustion engine from a 2.0 l and 110 kW engine with four cylinders to a 1.0 l and 44 kW engine with only three cylinders. Furthermore, downsizing stands for adjustments of the mechanical drive train so that the gearbox becomes redundant. Taken together the downsizing efforts lead to a cost reduction of about € 2000 compared to the reference vehicle purchase price.

The costs of the additionally needed electric components consist of costs for the power electronics and the battery, plus the costs for the electric engine itself. The costs for the electric engine and the power electronics with the wiring harness components sum up to about € 3100 (Biere et al., 2009; IES, 2008; Graham, 2001; Metric Mind Corporation, 2009; Weiss et al., 2000). Overall, this leads to an increase in the PHEV's purchase price of about € 1100, not accounting for the battery prices, which will be considered in the total cost analysis in section 4.4.

The fixed annual costs are influenced by vehicle taxes, wear of brakes, and maintenance costs. The annual savings for the PHEV of about € 215 occur mainly due to an assumed vehicle tax reduction of € 180, because of the lower CO_2 emissions[5], compared to the € 200 tax amount that is imposed on the reference ICE vehicle. This advantage of the PHEV regarding vehicle taxation is rather small compared to the benefits for hybrid and electric cars that are granted in other European countries. A few examples help to illus-

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[5] As from July 2009, the German vehicle tax system changed from being solely based on engine displacement to additionally accounting for CO_2 emissions for newly registered cars. The rates of the base tax (based on engine displacement) are € 2/100 ccm for gasoline and € 9.50/100 ccm for diesel, respectively. The CO_2 tax rate is € 2 per gCO_2/km, with a tax-exempted amount of 120 gCO_2/km (BMF, 2009). In 2012 and 2014 this threshold value will be lowered to 110 gCO_2/km and 95 gCO_2/km, respectively, following the EU guideline concerning vehicle emissions standards (EU, 2009b). In our calculation we assume that the PHEV considered is exempted from the tax on CO_2 emissions.

trate this point. In the UK, for instance, a bounty is offered of up to £ 5000 (approximately € 5750) per car. In Ireland, PHEVs and electric vehicles benefit from a vehicle registration tax relief of € 2500 and € 5000 maximum, respectively. Various regional Spanish governments subsidize the purchase of alternative fuel vehicles with € 2000-7000, and France grants an environment reward amounting to a maximum of € 5000 per vehicle (ACEA, 2011). Further incentives are granted, amongst other countries, in Austria, Belgium, Denmark, Italy, Portugal, the Netherlands, Luxemborg and Sweden, but also in non-European countries, such as the US, Japan and China.

PHEVs take further advantage of cost savings due to a decrease in maintenance activities. The downsizing of the ICE, for example, leads to a smaller amount of oil needed and a smaller air filter. In addition, the recuperation induces a lesser wear of the brakes. On the other hand, PHEVs will probably be equipped with low rolling resistance tires, causing additional costs. Nowadays, conventional cars are equipped with standard tires as the trade-off between possible driving dynamics and efficiency has been shifted towards higher dynamics. Nevertheless, most car manufacturers offer low rolling resistance tires (besides e.g. direct fuel injection or a start-stop function of the engine) as a part of their fuel efficiency concepts, which is considered in the scenario analysis.

Insurance costs strongly depend on the vehicles' technical specifications, such as age and engine power, as well as personal characteristics of the vehicle owner. But since these costs are influenced by too many factors for which reliable market data are not publicly available yet, they are not considered in our calculations, as already mentioned before. This argument also applies to possible monetary benefits that the PHEV owner might reap by providing V2G services with the car battery, since it will take some time until a smart grid is established in Germany that allows V2G to become viable at large scale.

4.4 Cost savings until 2020

The results from the previous sections allow us to give a first answer to two central research questions: (1) Is it cheaper for the average car user to own a PHEV instead of a conventional car?; and (2) Which battery size will lead to the lowest TCO?

As already discussed, our energy consumption model distinguishes between three different charging strategies: (1) charging at day, (2) charging at night, and (3) charging after each trip[6]. Furthermore, the TCO model distinguishes between three different types of battery with assumed capacities of 4, 12 and 20 kWh, respectively. In order to compare the annual cost savings over the entire lifetime for the vehicles studied with the initial expenditures, we calculated the net present values. To this end a discount factor for future expenditures and savings has to be determined. We chose a discount rate of 8%, as suggested by the Deutsche Bundesbank for investments of private car owners (Deutsche Bundesbank, 2009), and thus reasonably represents the opportunity cost of the purchase. Even though consumers generally would not invest in new automobile technologies unless the financial payback time is very short (Continental, 2009), which would motivate the use of a higher discount rate, we consider 8% as appropriate, because we are comparing the actual lifetime costs that a vehicle owner incurs, rather than the perceived cost-effectiveness.

As can be seen from Figure 4 the differences between the battery sizes have a minor influence only on the cost savings and thus are contrary to what we expected beforehand. A reason for this finding is the increased efficiency of the ICE in the range extender mode that by far dominates the impact of the possibility to drive longer distances with cheap electricity. Only in the long term and for a “charging at night” strategy, there is a noticeable spread in favor of a 20 kWh battery.

By considering these annual cost savings for a higher annual mileage, a different situation appears. In this case, the annual savings increase with different battery sizes and have a stronger impact than discussed beforehand. Contrary to this, a lower annual mileage implies a smaller spread between the different battery sizes.

[6] The possibility to recharge the battery after each trip presumes an area-wide public charging infrastructure, whose installation would be very costly. It can be expected, that these additional costs would then be passed on to the consumers by a surcharge on electricity prices, which would influence the cost-effectiveness of PHEVs and delay their break-even. In our calculations, we ignore these additional infrastructure costs.

For computing the total cost savings for PHEVs with different battery sizes, it is necessary to consider the corresponding battery costs. Due to the early state of market introduction, which implies great uncertainty about the battery prices, we consider two different price scenarios. In the first one, we assume a price of € 500/kWh, which is the estimated end-user price for lithium-ion high-power batteries in large-scale production (Wallentowitz et al., 2010). This leads to battery prices of € 2000 for the small battery, € 4000 for the medium-sized and € 10,000 for the large battery. In the second scenario, we take a price of € 1000/kWh, which is about the current end-user price for lithium-ion batteries (BCG, 2010). This corresponds to battery prices of € 4000, € 12,000 and € 20,000, which of course delays the break-even of the initial investment.

The payback periods for each battery size have been calculated by comparing the cumulated annual savings with the purchase price of the battery. The smallest battery, with a capacity of just 4 kWh, amortizes itself already after three to five years of usage, whereas the largest battery considered needs more than ten years for cost amortization. Because most owners of new cars on average only keep their vehicles for approximately 7.5 years, the battery should have been amortized within this period of time to make a positive business case (DAT, 2009; DAT, 2010).

The analysis shows that from a long-term perspective, there is a potential to reduce the TCO with a PHEV. Furthermore, a small battery of 4 kWh renders nearly the same cost savings as a 20 kWh system but costs significantly less and, therefore, can be amortized much earlier.

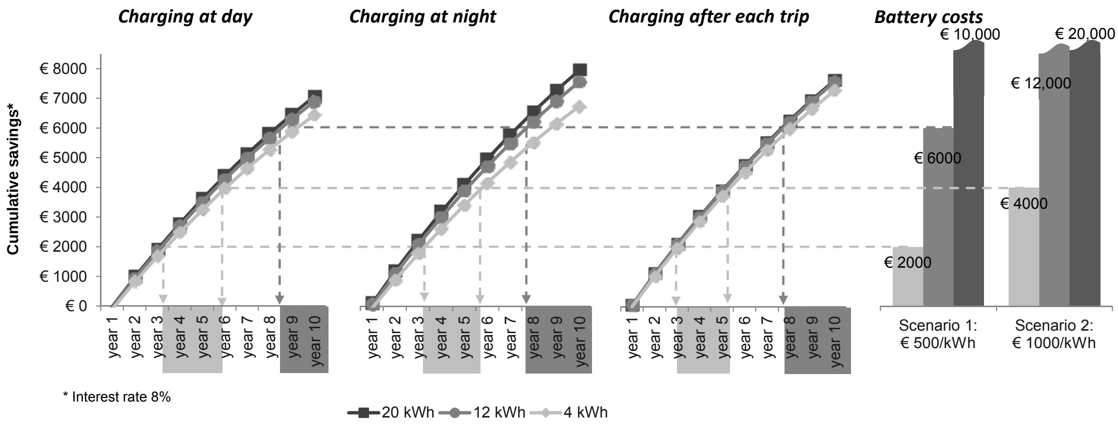

Figure 4. Cumulative annual cost savings and amortization periods (break-even durations are indicated by arrows) of a PHEV compared to an ICE vehicle, as a function of battery size (4, 12 and 20 kWh), battery costs and charging regime – the additional purchase cost of the PHEV is accounted for in the first year

The results for the PHEV cost amortization calculations for the different charging strategies are summarized in Table 1. It becomes clear that for the assumptions made the 20 kWh battery cannot be amortized over the time period of ten years considered, since the battery system costs are too high in comparison to the achievable annual cost savings. The 12 kWh battery may reach the breakeven point in the € 500/kWh scenario after 8-9 years.

Table 1 Amortization time of PHEV batteries regarding different battery sizes, battery prices and charging scenarios (in years)

Battery size	**4 kWh**		**12 kWh**		**20 kWh**	
Scenarios in €/kWh	**500**	**1000**	**500**	**1000**	**500**	**1000**
Charging at day	3	6	9	-	-	-
Charging at night	3	5	8	-	-	-
Charging after each trip	2.5	5	8	-	-	-

Note: “-“ indicates that amortization cannot be achieved within 10 years

4.5 Cost savings until 2020 for different engine efficiency scenarios

4.5.1 Lower efficiency of range extender

The comparison of the annual cost savings in the first scenario is based on the assumption that the end-user compares two cars with nearly identical performance figures. But since many (and not only green) consumers in Germany prefer small and fuel-efficient vehicles (Dena, 2010) we decided to vary engine efficiency in a scenario analysis, since this factor is significant for the calculated annual savings of a PHEV compared to an (optimized) ICE vehicle. Thus, on the one hand, the efficiency of the range extender was reduced by 30% and 50%, as the serial hybrid power train is an infant technology and might not reach its full potential immediately. On the other hand, with non-optimized recharge and usage strategies, the degree of efficiency may not reach the expected target values.

4.5.2 Technically optimized ICE

The second scenario was performed with the optimization of the conventional ICE in stages of 10, 20 and 30%, which seems very likely, as ICEs still offer a huge potential for fuel consumption reduction and even today plenty of technological measures exist in the market that could increase fuel efficiency and that are integrated in optimization packages offered by some original equipment manufacturers (OEM) for selected models at additional costs. Examples are the reduction of engine friction losses, direct injection, homogeneous charge (stoichiometric), stratified charge (stoichiometric/lean burn/complex strategies), downsizing with turbo charging, variable valve timing/control, variable compression ratio, and optimization of the cooling circuit and the auxiliary consumers. Furthermore, the optimization of the clutch and gearbox as the central part of the power train offers a non-deniable potential to reduce the fuel consumption and simultaneously increase the driving dynamics. In this respect especially dual clutches and a piloted gearbox with an intelligent shifting strategy are promising developments. Additionally, a huge technical potential is offered by the electrification of the power train, like the introduction of a start-stop function or an intelligent regeneration strategy.

Further technical measures, such as improved aerodynamic efficiency, weight reduction through the usage of advanced lightweight materials and low rolling resistance tyres, can reduce the energy consumption of ICE vehicles even further (Sharpe and Smokers, 2009). Overall, a technically optimized ICE vehicle might decrease the fuel consumption up to 30% but might also lead to less maximal power. This 30% reduction causes consumption values of 8.1 l/100 km for trips in urban areas and no more than 5.0 l/100 km for highway usage. These are characteristic values which are achieved by the newest, recently announced vehicles in the compact-class market segment targeted in our study.

This reduction in the energy consumption of the ICE vehicle leads to drastically increased durations for the standard PHEV to reach the break-even point, which can clearly be seen in Figure 5. For the owner of a car with the small 4 kWh battery the break-even has clearly moved to a usage period of more than five years. In the high battery price scenario, the break-even for the 4 kWh battery is reached after ten years. The larger battery sizes considered turn out to be uneconomical and inefficient, independently of the high or low price scenario, as the annual savings are in both scenarios insufficient.

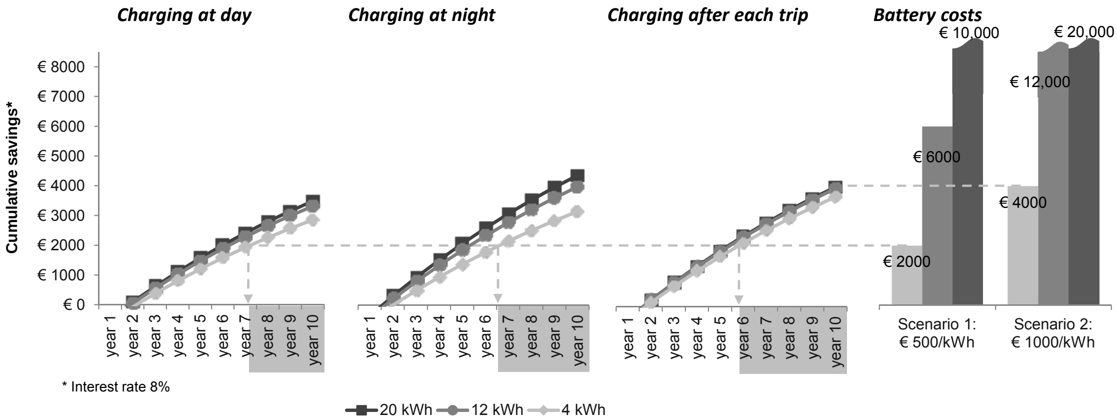

Figure 5. Cumulative annual cost savings and amortization periods (break-even durations are indicated by arrows) of a PHEV compared to an optimized ICE vehicle (-30% fuel consumption), as a function of battery size (4, 12 and 20 kWh), battery costs and charging regime – the additional purchase cost of the PHEV is accounted for in the first year

4.5.3 Slightly optimized ICE and non-optimized PHEV

In a further step, we compared a slightly optimized conventional vehicle (-10% fuel consumption) and a non-optimized serial hybrid technology vehicle (+30% fuel consumption). In this combined scenario the possible savings are about € 2270 and thus significantly lower in the once-per-day / night recharging scenario. In the recharging-after-each-trip scenario the savings are only reduced by € 1850, as can be seen in Table 2. The break-even for the 4 kWh battery system then lies between four and six years in the low price battery scenario, which would be still within the average duration of first-hand car ownership of new cars of about 7.5 years (DAT, 2009; DAT, 2010). Therefore, an ecologically- and cost-conscious adopter would still prefer the PHEV.

Table 2 summarizes the results of the different scenarios – lower efficiency of the range extender, technically optimized ICE, and slightly optimized ICE and non-optimized PHEV (combined scenario).

Table 2 Scenario analysis of a variation of the fuel efficiency

Factor	**Subscenario**	**Effects on cost savings**		
Charging strategy		**At day**	**At night**	**After each trip**
Lower efficiency of the RE	+30% (5.2; 5.8; 6.6 l/100 km)	-16.0%	-14.8%	-8.8%
		€ -1070		€ -650
	+50% (6.0; 6.7; 7.6 l/100 km)	-26.5%	-24.6%	-14.5%
		€ -1780		€ -1085
Optimized reference ICE vehicle	-10% (10.4; 7.6; 6.4 l/100 km)	-17.6%	-16.2%	-16.0%
			€ -1200	
	-20% (9.3; 6.7; 5.7 l/100 km)	-35.2%	-32.2%	-32.0%
			€ -2400	
	-30% (8.1; 5.9; 5.0 l/100 km)	-52.3%	-48.6%	-48.0%
			€ -3590	
Combined scenario	+30% RE -10% ICE	-33.5%	-31.0%	-24.8%
		€ -2270		€ -1850

Note: RE = range extender

4.6 Sensitivity analysis

In the previous section we analyzed the influence of a variation of the engine efficiencies on the TCO and the amortization time of a PHEV, leaving everything else unchanged. In contrast, in this section, the engine efficiencies are kept constant at their base levels (i.e. without lower efficiency of the range extender and optimization of the ICE), while all other parameter values are varied, in order to assess their influence on the cost savings of the PHEV compared to the reference ICE vehicle. The changes in the cumulated annual savings until 2020 are summarized in Table 3.

The most significant change within the TCO model is caused by a variation of the gasoline and electricity prices. By switching from the conservative to the optimistic gasoline price scenario, cumulative savings until 2020 rise from € 850 to € 1000, depending on the chosen charging strategy. Going along with this change, the break-even may be reached in the high price scenario nearly one year earlier for the medium-sized battery and a few months earlier for the small one. The change from a high electricity price development (€ 0.31/kWh in 2020) to a low one (€ 0.24/kWh in 2020) would result in additional savings of € 220 to € 410, respectively, which are mainly influenced by the different battery sizes. The magnitude of this change shifts the break-even only by about a few months.

By lowering the discount rate by 1%, future savings are weighted higher and increase the total discounted savings by € 330 (+4%). A change in the initial purchasing cost leads to exactly the same additional cost in each scenario, as no discounting is involved.

A change of the technical assumptions has a lower effect on the TCO. Changes of the degree of efficiency of the whole drivetrain, the usage of the auxiliary consumers or the vehicle weight impacts the resulting cumulative savings by less than 2% and, therefore, does not change the main results.

Table 3 Sensitivity analysis of the major parameter value assumptions except engine efficiency

Factor	**Variation**	**Effects on cost savings**		
Charging strategy		**At day**	**At night**	**After each trip**
Gasoline price scenario	Low ⇨ High	+12.4% € 848	+11.4% € 848	+13.2% € 988
Electricity price scenario	High ⇨ Low	+4.4% € 303	+2.8% € 213	+5.4% € 406
Discount rate	-1%	+4.5% € 303	+4.4% € 327	+4.4% € 329
Purchase costs	€ +1000		€ 1000	
Degree of drivetrain efficiency	+1%	+1% € 72	+1% € 69	+0.9% € 65
Consumption of auxiliary consumers	+100%	-0.8% € -52	-0.7% € -47	-1.3% € -92
Vehicle weight	-100 kg	+1.7% € 113	+1.4% € 103	+1.7% € 124

5 CO_2 emissions

In Germany, environmental considerations are a (very) important decision criterion in vehicle choice for 83% of potential car buyers (Dena, 2010). Additionally,CO_2 emissions are an economic factor in Germany, since they are considered in the vehicle taxation system and since the electricity supply sector is subject to the European Trading System (ETS) for CO_2. Therefore, the CO_2 balance of the concepts is discussed in this section.

The calculation of the CO_2 impact of the conventional ICE vehicle and the PHEV was conducted as follows. We multiplied the individual energy consumption with the corresponding CO_2 values, taking various electricity mixes into account, but without differentiating for the time-of-day of the recharge process and its impacts on the electricity generation portfolio[7].

According to the EU Directive 93/116/EC (EU, 1993) 2370 g of CO_2 are generated through the combustion of 1 l of gasoline. This means that with an average consumption of 9 l/100 km some 213 g CO_2/km are emitted. The basis for an emissions analysis for the electric drive train is the power generation sector. Due to the fact that a large portion of the German electricity generation is provided by coal-fired power plants (42.8% in 2009, cf. BDEW, 2010), the average CO_2 emissions are relatively high compared with the EU-15 generation mix (Öko-Institut, 2009). The German power generation sector emits 565 g CO_2/kWh (UBA, 2011), which for a specific consumption of 15 kWh/100 km leads to about 85 g CO_2/km on average. This is less than half of the emissions of the ICE car.

As can be seen from Figure 6, compared to the ICE vehicle the CO_2 emissions of the PHEV decrease independently of the energy production system considered. In this case the usage of the lignite technology leads to the highest CO_2 emissions, whereas renewable energies offer a maximum reduction of CO_2 emissions. About 88% of the emissions of the reference car could be saved if a battery with a capacity of 20 kWh is used.

The difference in CO_2 emissions regarding the battery sizes is also worth to notice. While the usage of the small battery is advantageous with regard to the emissions in the lignite scenario, there is a remarkable contrast regarding the use of renewable energies. Here the smaller battery causes emissions that are twice as high as the emissions of a vehicle with a 20 kWh battery. This is due to the fact that the combustion of gasoline in the ICE is less CO_2-intensive than the electricity generation in lignite-fired power plants, but leads to higher CO_2 emissions when electricity generation is "green".

The different charging strategies do not lead to significantly different CO_2 emissions when the German power mix is considered. However, with the strategy "charging after

[7] See Mazur and Madlener (2010) for a detailed study of the impact of the diffusion of 4 million PHEVs on the total emissions of power plants and vehicles with regard to the German energy mix, various charging scenarios, and various battery capacities.

each trip” it is possible to further reduce the CO_2 emissions, especially when CO_2-free electricity is used. We conclude that the electric drive train offers the possibility to drastically reduce CO_2 emissions compared to the reference car.

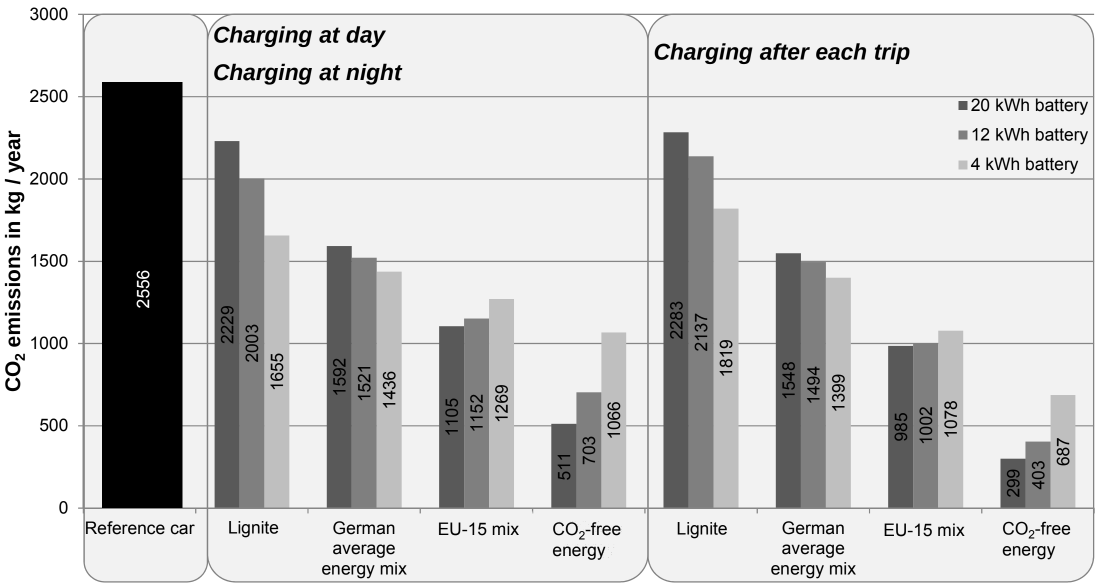

Figure 6. Impact of PHEVs in terms of CO_2 emissions (compared with standard ICE vehicles) – Assumptions: Lignite (1033 g CO_2/kWh), German average energy mix (650 g CO_2/kWh), EU-15 mix (357 g CO_2/kWh), cf. Öko-Institut (2009)

The discussed -30% optimization potential of a conventional ICE will lead to an annual CO_2 emission value of about 1800 kg/year. This is better than the CO_2 well-to-wheel balance of a PHEV that is recharged with electricity from lignite-fired power plants.

If the degree of efficiency of the electric power train together with the range extender is impaired, as described in section 4.5.3, then using a PHEV is more ecological compared to a highly efficient ICE vehicle only when CO_2-neutral electricity, such as from hydro and wind power, is used.

6 Summary and conclusions

Based on our assumptions about the daily and annual driving patterns, the development of energy prices until 2020, the vehicle size and horse power, the vehicle taxes, the differences in the maintenance and initial costs, and the efficiency of the electric components, we find that there is substantial potential to reduce the total cost of ownership of a

PHEV in comparison to a standard and even to an optimized ICE vehicle within the next few years.

Based on our model results, especially cars with smaller batteries (e.g. 4 kWh) are found to be cost-effective within less than five years. Larger batteries reduce the CO_2 emissions if they are charged with green electricity, but have significantly higher initial costs. In the standard scenario, for example, a 12 kWh battery system would become economical after a usage period of 8-9 years. To be competitive compared to conventional ICE cars, however, the break-even has to be reached at least within the average first-hand ownership time of the new car of about 7.5 years (DAT, 2009; DAT, 2010).

Concerning the recharging strategies we showed that the presented alternatives did not differ significantly. The over-night recharging strategy is the most economical way but needs an infrastructure and a billing system that is capable of supplying time-variant tariffs. In Germany, the installation of such a grid and metering infrastructure has only just begun and will take years to be completed. Such intelligent grid infrastructure offers the potential to use the battery in vehicle to grid systems in the future, which would support larger batteries, since ancillary grid services are partly paid for just being available and partly per kWh generated.

In our very simplified average calculation we also illustrated that the CO_2 impact of PHEVs is positive and that even small batteries offer some potential to reduce the CO_2 emissions compared to the reference car. With an increasing battery size it is necessary to use clean electricity to further improve the CO_2 balance.

Nevertheless, the results show that PHEVs with small batteries are close to cost-competitiveness and hence offer a chance to start the transition to full-electric mobility even in the presence of high battery prices. Thus, if the intention of the government is the acceleration of the diffusion of PHEVs, then their incentives should be designed to increase the adoption rate of PHEVs with a small electricity capacity. Looking at our results, a first step might, for example, be a state-wide consumer information program, aimed at increasing the awareness about the long-term benefits of PHEVs due to their lower fuel costs. Another measure could be to force the car manufacturers to label the gasoline and electricity consumption of their vehicles in a clear and easily understandable way, like the European energy label for domestic cooling appliances (EU, 1994).

How these results might change when (1) the deterioration of the battery is taken into account or (2) our analysis is widened to account for different driver categories with different driving profiles regarding trip length or annual mileage and/or the inner-city/rural/highway trip ratio and (3) different vehicle classes, leading to a change in size, weight, driving resistance, fuel consumption etc. is needed to be determined in future research.

Besides this analysis of the costs and benefits of electric vehicles in general and especially PHEVs, further research is needed to gain better insight into vehicle consumer preferences, since consumers normally do not assess the cost savings from energy-efficient technologies objectively. Only when the barriers that lead to consumer rejection of these new vehicle technologies are eliminated a major diffusion of electric vehicles can take place.

Finally, it should be pointed out, that the research done in this paper is highly dependent on the assumptions made, concerning the price developments of gasoline, electricity, power electronics, electric engines and batteries in the next couple of years. Since this research was completed end of 2009, some of the assumptions made turned out to be different in reality, while others stayed unchanged. For example, as already mentioned earlier, a mass production of PHEVs and electric vehicles still does not exist, so that there is still a lack of resilient market data on purchase price differences between PHEVs and conventional ICE vehicles in general, and the influence of single components, such as power electronics and batteries, on it in particular, so that the data from the literature on which our calculations are based are still valid. The same holds true for the stability of driving patterns of the average German car user. However, gasoline and electricity prices did not follow the paths (see footnote 3) we assumed in our conservative approach and rather increased faster over the last 1 ½ years. But since gasoline prices escalated faster than electricity prices this development should favor PHEVs compared to conventional ICE vehicles, making them more cost-effective and letting them break-even more quickly.

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