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Optimal size of PHEV batteries from a consumer perspective – estimation using car movement data and implications for data harvesting

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Abstract

Due to expensiveness of PHEV batteries, the dimensioning of the batteries is very important. We derive the marginally optimal size from a consumer economics perspective and show that a crucial factor for optimal size and profitability is the marginal annual recharging frequency. We apply the analysis to a small set of Swedish vehicle movement data and demonstrate that the resulting optimal battery is highly dependent on the specific movement pattern of the individual car. We conclude that it is now urgent for the continued development, planning, and estimates of proliferation and impact of PHEVs, that statistical data, today mostly lacking, for the movement patterns of individual vehicles are assembled.

Keywords: data acquisition, market, modelling, PHEV (plug in hybrid electric vehicle)

1 Introduction

The ongoing electrification of passenger vehicles in the form of hybrid electric vehicles (HEV) enhances the vehicle energy efficiency by facilitating increased brake energy recovery, utilization of more efficient regions of the engine map, and downsizing of the engine. A natural extension of the hybrid vehicle, highlighted by the recent battery development, is the plug-in hybrid electric vehicle (PHEV). This car with a larger battery rechargeable from the grid makes possible electricity as an energy source for the car, and, when in electric drive mode, a much higher energy conversion efficiency in the car itself. The total effects, for instance from a climate change point of view, will of course depend on the specific electricity production. The electricity systems have large possibilities to become more CO_2-neutral to a reasonable cost penalty, though, why possibly the electrification of the car and the integration of the mobile and stationary sectors may be a viable option. This is also supported by modelling of cost-efficient pathways of the global energy system to complying with stringent climate targets [1, 2].

Whatever the total energy and climate properties, also the car owner economy is important for any viability. For PHEVs there is no revenue to battery capacity from security of range due to the available backup from the fuel engine and storage. Therefore, disregarding maintenance, insurance, etc, the purchase price and the cost of driving are the major factors determining the economics. But the economy depends not only on the PHEV itself, but on the alternatives. Whatever the alternatives, any PHEV must at least be competitive with other PHEVs having other sizes of the battery, including no battery rechargeable from the grid, i.e., a comparable HEV.

Here we investigate what is an optimal PHEV battery from a car consumer point of view dependent on performance, costs and car movement pattern. Finally we discuss some possible implications of the results.

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2 Method

First we derive an analytical expression for the optimal battery for a PHEV dependent on performance, costs and the car movement pattern. We then perform a Monte Carlo analysis of the optimal battery size when applied to a sample of measured Swedish individual car movement patterns.

2.1 Utilization of the battery in a PHEV charging once daily

We first derive some expressions for the possible utilization of a battery that is recharged once daily, for instance, at home during the night after being used during the day.

The car has a movement pattern {f(x)} over the year describing the frequency f(x) for a daily distance x. (The definitions and the units used for the variables are given in Nomenclature.) We have for the distribution the number of days with daily distances ≤ d and with any distance, respectively

$$F(d) = \sum_0^d f(x) \qquad (1)$$

$$F(\infty) = \sum_0^\infty f(x) = 365 \qquad (2)$$

We get the annual distance driven in days with x km driven, s(x), as

$$s(x) = xf(x) \qquad (3)$$

For the corresponding accumulated annual distance S now holds

$$S(d) = \sum_0^d s(x) = \sum_0^d xf(x) \qquad (4)$$

$$S(\infty) = D \qquad (5)$$

The share of annual accumulated distance driven in days with distance driven x ≤ d becomes

$$r_S(d) = \frac{S(d)}{S(\infty)} = \frac{S(d)}{D} \qquad (6)$$

If we denote with d_e the maximum daily distance driven on electricity, i.e., the all-electric range (AER), we get the annual distance driven on electricity

$$S_e(d_e) = S(d_e) + \sum_{d_e+1}^\infty d_e f(x) = S(d_e) + d_e[F(\infty) - F(d_e)] \qquad (7)$$

We get the marginal annual distance driven on electricity per AER [–], which also is equivalent to the marginal annual recharging frequency, as

$$S_e^{'}(d_e) = S^{'}(d_e) + 365 - F(d_e) - d_e F^{'}(d_e) = 365 - F(d_e) = \sum_{d_e+1}^\infty f(x) \qquad (8)$$

For $r_e(d_e)$, the electric drive fraction (EDF), i.e, share of annual accumulated distance driven on electricity, we get

$$r_e(d_e) = \frac{S_e(d_e)}{S(\infty)} = \frac{S_e(d_e)}{D} \qquad (9)$$

The all-electric range d_e is, of course, dependent on the battery size and utilization:

$$d_e = U/e_e = \beta B/e_e \qquad (10)$$

where B = battery capacity, β = SOC_{max}-SOC_{min}, U = utilized capacity = βB, and e_e = electric energy [kWh] used per km driven.

We assume that the car first is utilizing only battery energy and then turns to 100% fuel driven propulsion. We then have

$$d_e = U/e_e = \beta B/e_e \qquad (11)$$

We can now derive the average state of charge for the battery in the end of the day after being used and the possible charging. Denoting SOC_u the end-of-day state of charge of the utilized interval of the SOC [–]; $SOC_u \in [0,1]$, and $S\hat{O}C_u$: the expected end-of-day state of charge [–], we get

$$S\hat{O}C_u = E[SOC_u] = \frac{1}{F(\infty)}\left[\sum_0^{d_e}(1-\frac{x}{d_e})f(x) + \sum_{d_e+1}^\infty 0\cdot f(x)\right] = \frac{1}{365}\sum_0^{d_e}(1-\frac{x}{d_e})f(x) = \frac{1}{F(\infty)}\left[F(d_e) - \frac{S(d_e)}{d_e}\right] \qquad (12)$$

The number of equivalent full annual charges, $N_C(d_e)$ becomes

$$N_C(d_e) = (1 - S\hat{O}C_u)F(\infty) = [1 - \frac{1}{F(\infty)}(F(d_e) - \frac{S(d_e)}{d_e})]F(\infty) = F(\infty) - F(d_e) + \frac{S(d_e)}{d_e} = \frac{S_e(d_e)}{d_e} \qquad (13)$$

The battery utilization factor η, i.e., N_C/ max N_C, is

$$\eta = N_C/\max N_C = 1 - S\hat{O}C_u \qquad (14)$$

2.2 The economics of marginal battery capacity

We now derive an expression for the optimal battery capacity for the given movement pattern For simplicity we assume that the price of fuel p_f and electricity p_e are equal (= p) for the customer, which means we can introduce an common energy price. This reasonable under today's West European condition where in many countries the

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fuel price for cars and the electricity for household costumers including taxes is around 1.2-2 \$/litre and 0.10-0.20 \$/kWh, respectively [3,4] (1€=1\$ assumed). The annual marginal revenue and cost, respectively, are

$$i(d_e) = S_e'(d_e)p(e_f - e_e) = (S_e(d_e+1) - S_e(d_e))p(e_f - e_e) \tag{15}$$

$$c(d_e) = \alpha\beta^{-1}C'(B)e_e \tag{16}$$

where α = annuity, C(B) = cost of battery, e_f and e_e energy use per distance in fuel and electric mode, respectively. It is profitable to expand the battery as long as $i(d_e) > c(d_e)$, i.e., when

$$S_e'(d_e)p(\frac{e_f}{e_e} - 1) > \alpha\beta^{-1}C'(B) \tag{17}$$

or as long as the marginal annual distance driven on electricity, is

$$S_e'(d_e) > \frac{\alpha\beta^{-1}C'(B)}{p(\frac{e_f}{e_e} - 1)} \tag{18}$$

The minimum number of marginal annual charges for which profitability holds, is thus

$$n_{Cp} = \frac{\alpha\beta^{-1}C'(B)}{p(\frac{e_f}{e_e} - 1)} \tag{19}$$

The corresponding optimum value of all electric range d_e for which profitability is maximized, is now

$$d_{ep} = d_e \big| S_e'(d_e) = n_{Cp} \tag{20}$$

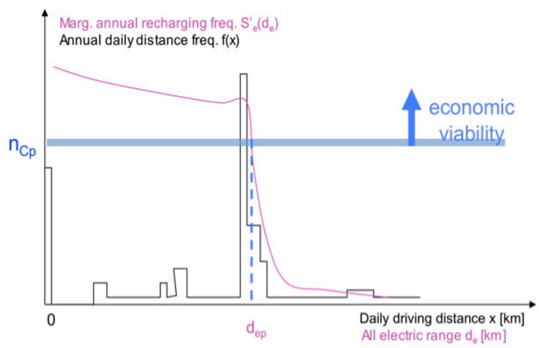

Figure 1: Optimal PHEV battery size d_{ep} for a specific vehicle characterized by its frequency of daily distance driven (example).

The value of d_{ep} depends on the annual movement pattern {f(x)}. For illustrative purposes an example is given in Fig. 1. In this case the marginal annual recharging frequency drops sharply after the peak in the daily driving distance frequency f(x). The optimal battery size is determined by the crossing of the n_{Cp}-line, implying an optimal battery size d_{ep} close to the sharp drop.

For a given annual distance driven D, the extreme values of d_{ep} are

$$0 \le d_{ep} \le D / n_{Cp} \tag{21}$$

If the number of vehicle use days is too low, there is no profitability for any d_e

$$d_{ep} = 0 \quad \text{if } N_u < n_{Cp} \tag{22}$$

where N_u is annual days of vehicle use, i.e., $F(\infty)$-$F(0)$. The maximum attainable profitable value of d_{ep} is achieved for a movement pattern for which the annual driving distance is distributed equally over n_{Cp} days

$$d_{ep} = D / n_{Cp} \text{ if } f(x) \ne 0 \text{ iff } x = D / n_{Cp} \tag{23}$$

2.3 Data

2.3.1 Car movement patterns

We apply the analysis to a small Swedish car movement data set covering the driving (of possibly one of the cars) in 30 families for about two weeks each in the autumn of 1998 [5]. The cars where all localized in or in the vicinity of Västerås, a mid-sized Swedish town. The car position where logged in two dimensions with 2 Hz by GPS equipment. Together the measured driving covered more than a year and about 18 000 kilometres. (Also a lot of vehicle parameter where logged such as speed, gear changes, motor parameters etc, and used to facilitate modelling of emission in real driving. This also means that there were actually only five different cars, which were especially prepared and replaced family cars of the same size during the measurement period.)

The dataset used here is a portion of the above data, in which the position could be connected to a road map, the measured position was of enough length and quality, etc, prepared for studies of the connection between driving behaviour, street characteristics and emission [6,7]. It covers 11 175 kilometres from 29 of the families for between 12 and 16 days. Because this study focuses the total daily driving, the driving of the first and last day for each family period is put together (The change of family where done roughly at the same time of the day.) This results in altogether 394 days of driving. From this the yearly driving of the families is derived by scaling to 365 days. Thus we assume that for each family the driving in the measurement period characterizes the whole year. It is important to note, though, that while the total driving in the original data set is reasonably representative for Swedish driving condition when

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it comes to total distance (≈ 16 000 kilometres per car and year compared to about 14 000 kilometres in average in Sweden, and up two 22 000 for the youngest cohorts [8]. The total driving in the selected portion used here is low in comparison (11 175*365/394 ≈ 10 300 kilometres per car and year).

2.3.2 Cost and performance parameters

The car movement data are used to derive car movement pattern characteristics such as the marginal annual recharging frequency S'_{de} (eq. 8) and the electric drive fraction r_e (eq. 9). We combine this with estimates of the limit for profitable (or optimal) marginal annual recharges n_{Cp} (eq. 19). We apply a Monte Carlo (MC) analysis to the value of n_{Cp} in order to estimate a possible distribution in optimal values and the implication of uncertainty in the underlying parameters, see Table 1. In the MC analysis the varied parameters are assumed to be distributed linearly (i.e., having equal probability) within their uncertainty intervals.

For the annuity α, applied to the payment of the battery, we assume a base case value of = 0.15. This corresponds to, for instance, ≈ 8 yrs payback period and a discount rate of 5%. The uncertainty interval for the annuity is set to 0.10 to 0.20, corresponding to, for instance, about 12yrs/3% and 6 yrs/5%, respectively.

Table 1: The performance and cost parameters varied in the Monte Carlo estimation of profitable marginal annual recharges (min and max values). Values given for a base case as well.

Parameter	Min value	Base case	Max value
Annuity α [-]	0.10	0.15	0.20
Depth of discharge β [-]	0.5	0.8	0.9
Marginal battery cost $C'(B)$ [$/kWh]	150	250	400
Energy price p [$/kWh]	0.10	0.16	0.25
Specific energy use quota e_f/e_e [-]	1.94 = 0.29/0.15	2.67 = 0.40/0.15	3.33 = 0.40/0.12

The cost of marginal capacity of the battery is in the base case set to C'(B) = 250 $/kWh. This is in agreement with the USABC goal for PHEV high energy-to-power battery system development [9]. 150 $/kWh assumes that further development may give even lower cost of the batteries in the future. The uncertainty of future costs is still large. Today's cost is around 1000 $/kWh [10]. The maximum future value is set to 400 $/kWh, which is roughly a halving of today's cost.

A battery capacity utilization or depth of discharge (DOD) of $\beta = 0.8$ is often assumed to be both possible and necessary to achieve for viability of PHEVs. According to [11], a battery DOD of 0.9 is claimed by some battery manufacturers to be possible to reach. However the trade-off today between lifetime and DOD means that concerns have been raised over possible future large DOD. For instance, the Chevrolet Volt PHEV planned for introduction in 2010 is expected to use only 50 % of the battery capacity ($\beta = 0.5$), which is also the minimum value assumed here.

For simplicity we have assumed equal consumer price for fuel and electricity and a base case of $p = p_e = p_f = 0.16$ $/kWh, which corresponds to the today's West European gasoline price and household electricity price level [3,4]. An interval of 0.10 to 0.25 $/kWh is assumed for future energy prices.

For a PHEV the profitable marginal recharging frequency n_{Cp} is also influenced by the relative energy efficiency ("tank to wheel" efficiency, TTW) of the electric and fuel mode. A base case value of 2.67 corresponds to, for instance, an efficiency of $\eta_e = 0.8$ (TTW) in electric mode and $\eta_f = 0.3$ in fuel mode (≈ Toyota Prius II in EU test drive cycle, NEDC, (own estimates)). Corresponding energy use values could be, for instance, $e_f = 0.4$ kWh_f/km (≈ 4.4 litre gasoline/100 km) in fuel mode and $e_e = 0.15$ kWh_e/km for the electricity mode, respectively, and an assumed delivered energy to the wheel of 0.12 kWh/km, which is reasonable value for a medium-sized car today on NEDC (own estimates). Examples of possible energy use values corresponding to the minimum and maximum values, slightly less than 2 and 3.33, respectively, are also suggested in Table 1, assuming relative increases in the fuel and electric mode, respectively.

3 Results

3.1 Possibilities for recharging and driving on electricity

The various car movement patterns give rise to different possibilities to recharge their batteries.

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Fig. 2 plots the resulting marginal annual recharges $S'_e(d_e)$ (eq 8) as a function of the size of the battery expressed as the all electric range d_e. (Note, the assumed condition here of charging once daily.) For a given battery capacity, S'_e varies considerably between the cars dependent on their specific movement pattern. The S'_e is monotonically decreasing with range. The maximum value is 365 reached for some of the cars (meaning that they have been driving in all days in the measurement period). For some it is as low as 150. The maximum variation, around 0-300, is achieved for a range of around 20-30 km. For cars driving less than this distance any day, the S'_e is zero, i.e, they can't fully recharge the battery any day and the utilization of the marginal battery capacity is zero. For large batteries the marginal utilization always goes to zero or very low values. Long distance daily driving happens for most cars only occasionally.

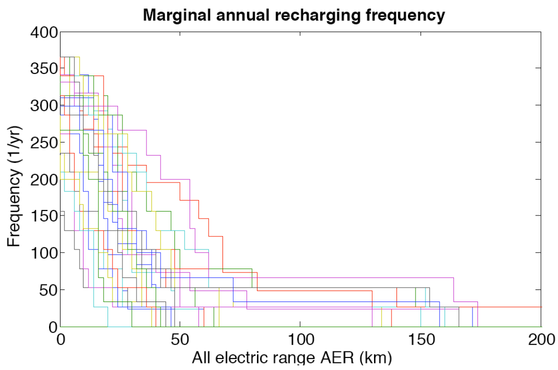

Figure 2: The marginal annual recharging frequency S'_e as a function of the all electric range AER d_e for the 29 different car movement patterns.

The high frequency reached here for long distances for some cars, is actually due to one or two day's driving during the measurement period, and the subsequent scaling to one year. The representativeness of this is not clear. However, it is obvious that the individual pattern will be smoothed out if measured for a longer period. The maximum measured daily distance was over 300 km.

An important parameter for PHEVs is the share of the distance covered by the electric propulsion. The resulting electric drive fraction, r_e (eq. 9) is shown in Fig. 3. The r_e increases monotonically with the battery capacity and reaches value of 1 when the capacity is enough for supplying all daily driving. For cars occasionally driving longer distances, the fraction increases less quickly with the capacity.

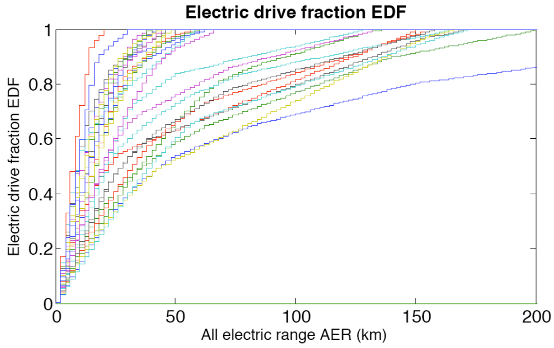

Figure 3: The electric drive fraction r_e as a function of the all electric range d_e for the 29 different car movement patterns.

3.2 Optimal battery and electric drive fraction

The effect of the variation in the parameters determining the profitable marginal annual recharges n_{Cp} (eg. 19) is given in Fig. 4 as an histogram for the 10 000 values generated in the Monte Carlo simulation.

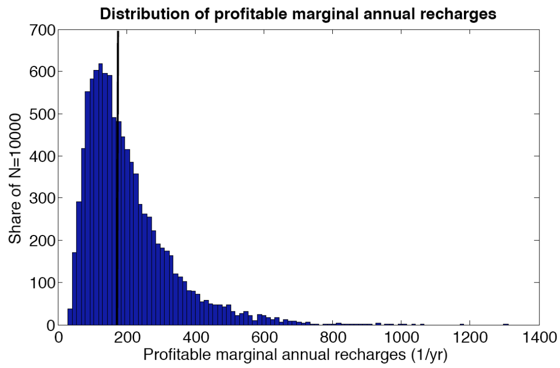

Figure 4: The Monte Carlo distribution of profitable marginal annual recharges n_{Cp}. The vertical line represents the value for the base case, ≈ 176 marginal recharges per year.

The minimum and maximum values possible are about 20 and 1700, respectively, but values closer to these than a factor of two are rare. For values of n_{Cp} larger than 365, reached in about 10 % of the cases, the recharging frequency requirements are so high that there is no profitable battery capacity whichever the movement pattern (still assuming recharging once daily). The value for the base case, 176 marginal yearly recharges, is also shown. This value implies that in this case a profitable capacity is such that it roughly covers workday commuting.

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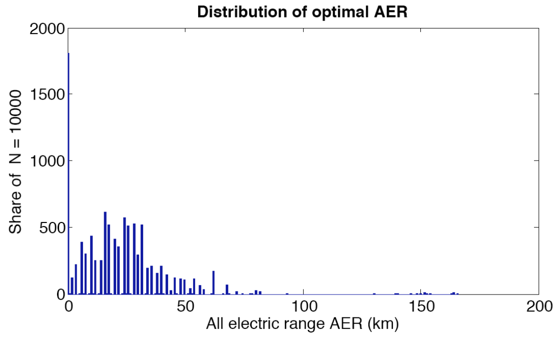

Figure 5: The distribution of optimal battery measured as AER for the Monte Carlo distribution of profitable marginal annual recharges for the 29 different car movement patterns.

The distribution of the optimal battery capacity for different movement patterns subject to the simulated possible variation in the profitable marginal annual recharges n_{Cp} is shown in Fig. 5. (The distribution has been normalized to 10 000.)

The optimal battery size varies considerably. In 18 % of the cases there is no profitable battery. This is due to a combination of high requirements on recharging frequency for profitability (Fig. 4) and specific movement patterns with low marginal recharging frequency already at low battery capacity (Fig. 2). The majority of the optimal all electric ranges are below 50 km with a peak around 20-30 km. (It should be reminded again, though, that the overall yearly driving per car is here somewhat lower than in average Swedish driving.)

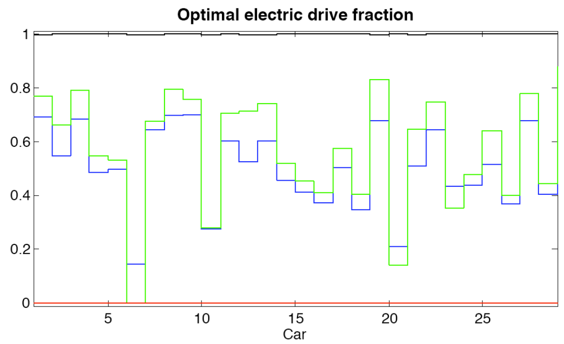

Figure 6: The optimal electric drive fraction (EDF) for profitable marginal annual recharges for the 29 different car movement patterns: The expected EDF for the Monte Carlo distribution (*blue*); the optimal EDF for parameter values corresponding to base case (*light green*); min profitability (*red*); and max profitability (*black*).

The resulting expected values for the optimal electric drive fraction for the 29 different families are depicted in Fig. 6. The expected EDFs vary between 0.1 and 0.7, but with most of them in the interval 0.35 to 0.7 and with an average value of around 0.5. Obviously the shown differences between the cars are due to the variations in the specific movement patterns.

Figure 6 also gives optimal electric drive fractions for specific parameter choices. The optimal EDFs for *base case* (Table 1) vary with the movement patterns between zero and slightly more than 0.8. For extreme parameter values, i.e., combinations corresponding to *maximum* and *minimum* profitable marginal annual recharges, the optimal EDFs are zero and (close to) one, respectively, independently of the driving patterns.

4 Discussion

In the analysis in this paper we have derived an expression for the optimal battery capacity for PHEV. We applied it to measured different car movement patterns, while introducing uncertainty in the performance and cost parameters underlying the optimality. This resulted in a broad distribution of optimal battery capacities and electric drive fractions, illustrated in Figs. 5 and 6.

The analysis introduced some simplifications. We assumed a simple linear model for the PHEV in which only the battery size and cost varied linearly with the all electric range. This can be reasonable at large battery sizes, but for small sizes, such as power requirement may influence the dimensioning and costs. Higher specific costs for smaller batteries may give lower marginal capacity cost pushing the optimum towards higher capacities. Power requirements for small batteries may favour a blended discharging mode instead of a pure electric mode as assumed here. This lowers the electric propulsion share and decreases the marginal battery revenues.

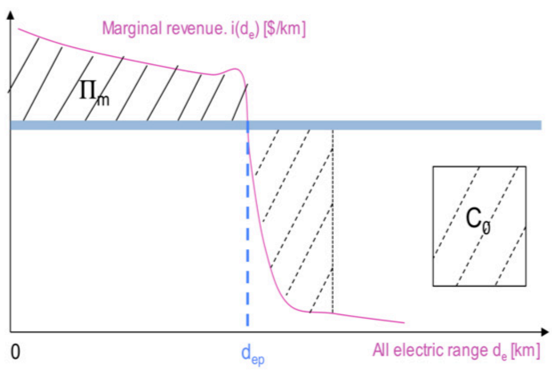

Figure 7: The profit corresponding to the PHEV example in Fig. 1 is the hatched area (negative for $d_e > d_{ep}$). Total positive economics requires that $\Pi_m > C_0$, an assumed initial cost.

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Going from HEV to PHEV will require initial costs in the form of equipment for charging. For the PHEV, especially when it should be possible to drive in all electric mode, it is required, compared to an HEV, a new dimensioning also of electric components other than the battery, introducing further initial costs. The total economics, as different from the marginal economics discussed here, may very well be such that the PHEV is economically inferior to the HEV although there is a local profit maximum, see Fig. 7 for an illustration.

The assumption of charging only once daily is another simplification. Charging more than once a day, for instance, besides at home also at the working place, will increase the marginal recharging frequency, but also reduce the distance driven between chargings resulting in a smaller but more profitable optimal battery. (This will also increase the battery cycling during the car lifetime.)

Although not further discussed here, the result of the study may be of importance and have implications for car dimensioning, possible business models and initial deployment. It can be argued that it should be considered to dimension the PHEVs individually through a flexible system for battery size adaptation, which can be individually adjusted, also over time, and, for instance, be adjusted when major changes in movement patterns take place. How this possibly can be achieved in practice will require further investigation, though. The flexibility requirement may also favour a business model in which the battery is leased to the car owner, which may want to minimize the risks and inconvenience associated with battery ownership and potential adjustments. The spreading of PHEV already at today's costs is facilitated if the early deployments have a high utilization of the batteries, i.e., a high marginal recharging frequency. Recharging possibilities at selected working sites could be one way of supporting this.

The results show that a crucial factor for optimality of the consumer economics is the marginal annual recharging frequency for the battery. For instance, in the base case, with current European consumer energy costs level and future targeted costs on battery, we calculated, that the optimality is achieved for a marginal recharging frequency in the range of 150-200 times a year. To achieve an optimal marginal recharging frequency, in this case, the battery has to be adapted such that the daily commuting or driving of similar frequency are covered, neither so much larger nor smaller.

The result of the study implies that a very important factor is the car movement pattern over time. The specific pattern is crucial for the car economy as well as the dimensioning of the car. Unfortunately, currently available data on transportation seldom give details on the distribution of specific car movement patterns, though. For instance, for transportation statistics in Sweden, extensive travel habit data are gathered based on the movements of individual persons for one day [12]. This data lack information on the movement of the car, which the individual utilizes (e.g., it can have been used during the day by other persons also, and several cars can have been used by one person). Data are also lacking on how a car's daily movements are distributed over days and over longer periods such as seasons and years and even between years, which are crucial for estimates of the possible economic viability of PHEVs. Insufficient data have been and are still used to perform estimates of the possible range and share of electric propulsion for fleets of PHEVs [e.g., 1,2,10,11,13,14,15].

5 Conclusions

Today and perhaps also still in the future, the relatively high battery costs for PHEVs imply that an optimal battery size is important factor for economic viability. The optimal size is highly dependent on the possible marginal annual recharging frequency and therefore on the single car's specific movement pattern. We conclude that for the further development and deployment of plug-in hybrid electric vehicle, data and statistics for the distribution of daily movement patterns for individual cars are urgently needed and need to be assembled.

Nomenclature

x : daily distance driven [km]

$f(x)$: annual number of days with daily distance driven x [–]

$\{f(x)\}$: annual movement pattern

$F(d)$: annual number of days with distance driven $x \le d$ [–]

$s(x)$: annual distance driven in days with x km driven [km]

$S(d)$: annual accumulated distance driven in days with distance driven $x \le d$ [km]

D : annual distance driven [km]

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$r_S(d)$: share of annual accumulated distance driven at days with distance driven $x \le d$ [–]
d_e : maximum daily distance driven on electricity, i.e., the all electric range (AER) [km]
$S_e(d_e)$: annual distance driven on electricity [km]
$r_e(d_e)$: the electric drive fraction (EDF), i.e, share of annual accumulated distance driven on electricity [–]
B : battery capacity or size [kWh]
SOC : state of charge [–];
β : SOC_{max} - SOC_{min} = ΔSOC = DOD, the depth of discharge, i.e., maximum utilized share of the total battery capacity [–]
U : maximum utilized battery energy [kWh]
η : the battery utilization factor, i.e., N_C/ max N_C
SOC_u : end-of-day state of charge of the utilized interval of the SOC [–]; $SOC_u \in [0,1]$
$\hat{SOC}_u$: expected end-of-day state of charge [–]
$N_C(d_e)$: the number of equivalent full annual charges [–]
p_f : customer fuel price [\$/kWh]
p_e : customer electricity price [\$/kWh]
p : energy price, here equal to p_f and p_e, assumed equal [\$/kWh]
e_f : fuel energy needed in fuel mode per distance [kWh/km]
$i(d_e)$: marginal annual revenue of all electric range [\$/km]
$c(d_e)$: marginal annual cost of all electric range [\$/km]
α : annuity [–]
C(B) : cost of battery with capacity B [\$]
n_{Cp} : the minimum number of marginal annual charges for which profitability holds [–]
d_{ep} : the maximum value of all electric range d_e for which profitability holds [km]
N_u : annual days of vehicle use [days]
$\hat{B}(d_{ep})$: optimal battery size, i.e., the battery size corresponding to maximum profitable all electric range [kWh]
$\hat{r}_e$: optimal electric drive fraction, i.e., $\hat{r}_e \equiv r_e(d_{ep})$ [–]

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