Conflicting interests in defining an 'optimal' battery size when introducing the PHEV?

Lars-Henrik Kullingsjö[1], Sten Karlsson[2], Frances Sprei[3]
Energy and Environment, Chalmers University of Technology
Gothenburg, SE-41296, Sweden
[1]larshenr@chalmers.se, [2]sten.karlsson@chalmers.se, [3]fsprei@chalmers.se

Abstract

The PHEV is an interesting option for reducing greenhouse gas emissions from transport or to increase energy security without losing performance in car operation. However finding an optimal battery size is of great importance for the overall economic and environmental performance of the PHEVs. This study investigates the resulting vehicle design, and fleet composition and performance when optimising the PHEV battery with respect to different objective functions possibly reflecting different actors' interest: number of PHEVs, cumulative cost savings and share of electric driving respectively under various assumptions concerning policies and costs. A recently available data set of car movements, containing 445 privately driven Swedish cars that have been measured with GPS-equipment for 1-2 months each is utilized to get a representative car fleet. We find that the battery size and fleet performance are heavily influenced by not only the choice of objective function for the optimization but also by its interaction with the cost structure and performance requirement in the transition from an energy efficient fuel-driven car to a PHEV. The effect of different policies may also vary depending on these conditions and may favour various actors' interests differently. We conclude that these aspects are important to consider both when designing vehicles and when formulating policies for the introduction of PHEVs.

Keywords: PHEV, battery, policy objective, subsidies

1   Introduction

A plug in hybrid electric vehicle (PHEV) has, in contrast to the energy-efficient conventional/ hydrid car, the capability to replace a major share of the fuel with electricity from the grid. In addition the PHEV does not suffer from limitations in range, which is thought to be one of the major disadvantages of the fully electric vehicle. This makes the PHEV an interesting option to for example reduce greenhouse gas emissions from transport or to increase energy security without losing performance in car operation.

The battery size is important since it together with the usage and charging patterns of the car will determine how large share of the driving that will be done with electricity, which influences both the economic viability and the environmental performance of the car. Earlier studies have used available data on individual car movements or various mileage statistics to find an optimal battery size for a PHEV [1], [2], [3]. Examples of objective functions used in these studies are

minimization of the total cost of ownership (TCO) for car users, and maximization of greenhouse gas emission reductions.

The goals behind the objective functions are not in general easily comparable. It is for example difficult to evaluate the societal gain from increased fuel security compared to a decrease in cumulative cost savings among the users. Different stakeholders value the outcome differently since they have different interests. Most car owners would probably favour a lower TCO over a high share of electric driving, while maximising driving on electricity could be seen as more beneficial for the society at large, since this can imply lowered emissions of greenhouse gases and increased energy security. Car manufacturers are generally interested in selling more cars as long as they can make money, and can therefore have reasons to position their brands in electromobility and specifically plan for increased sales of PHEVs in reaction to anticipated future changes in market conditions and energy/fuel/emissions regulation. It is therefore of interest to analyse the implications of different goals and methods to find an optimal battery size under various conditions.

The aim of this study is to analyse how the choice of objective function will influence the resulting optimal battery size, the fleet TCO savings, electric drive fraction, and number of PHEVs, and how this may be affected by various prerequisites for electromobility in the form of costs, possible subsidies and driving patterns.

Driven to a large extent by the increasingly stricter regulations on fuel use and CO_2 emissions, the on-going trend towards more fuel-efficient cars have led to among other things various degrees of hybridization of the driveline. A "conventional" vehicle (CV) is today difficult to define as the non-hybridized car when soon almost every car has at least a stop/start system and a continuum of models up to full hybrids are successfully marketed and sold.

Some car manufacturers have now also introduced PHEVs to the market. They differ both concerning design and connection to the brands' ordinary car models. For example, the Toyota Prius PHEV fully builds on the Prius, a since long produced gasoline HEV-only model, specifically designed both when it comes to body and the fully integrated series/parallel hybrid driveline. For the PHEV, the HEV battery has been exchanged for a small PHEV battery with an electricity-only range of moderate 20 km, while the rest of the driveline is kept intact.

Volvo has no hybrids but is offering the V60 PHEV built on their front wheel drive V60 model with a powerful diesel engine. A completely separate parallel electric driveline is fitted to the rear axle, while a generator is added to the engine in the front. Although powerful, the electric driveline has less than a third the power of the engine-powered one, or 50 kW compared to 158 kW. The PHEV battery has a range of around 50 km. The General Motors' Chevrolet Volt/Opel Ampera has a range on electricity of around 60 km. It is a series PHEV, that is, a powerful fully battery electric vehicle with the reasonably small fuel engine only working as a range extender with no mechanical connection to the wheels. The electrical components are therefore necessarily designed for electric drive only and for meeting all the performance requirements on the driveline. The vehicle is a new model and exists only as a PHEV and with its own design not very similar to any other vehicle in the GM family, whether hybrids or not. Currently there are apparently different designs of a PHEV and different ways of position it in relation to the parallel development of fuel-efficient alternative conventional/hybrid cars.

Depending on the market perception of both how a PHEV should be designed and the requirement on its electric driveline, as well as of what the alternative efficient fuel-propelled car looks like, it is therefore possible that the transition from the fuel-efficient conventional/hybrid car (denoted just HEV in the continuation) to the PHEV may involve a small or a large change of the electric driveline and its performance and thus imply, besides the extra costs for the larger battery a small or a large initial investment corresponding to the degrees of technical change. At a minimum a charger and extra cabling is added.

The component costs themselves for the electrified vehicles may also change with time due to market expansion and learning. For instance, the most important of them, the cost of the battery, has decreased considerably in the last years.

Other conditions may change as well. For instance, various kinds of subsidies for support of electrified vehicles. Although so far the different PHEV models have each only one size of their battery, there are on the market, as exemplified above, PHEV models available with different electric ranges. Different policies can to various degree reward or discourage the various battery sizes and thus affect the different models and brands differently.

There are a number of different schemes for subsidizing PHEVs and BEVs. Most of these are independent of battery size or capacity. The most prominent exception is the USA where the tax credit is based on the battery capacity of the vehicle starting from $2500 for 4 kWh. The credit increases with each added kWh up to $7500. The Nissan Leaf and the Chevy Volt are both eligible for the full tax credit while the Toyota Prius PHEV receives $2500 [4]. Additional subsidies exist in some states: e.g., in California PHEVs are eligible for a rebate of $1500, while BEVs receive up to $2500 depending on range [5]. In Europe the subsidies are flat and the threshold level is determined by tail-pipe CO_2 emissions per km. In Sweden e.g., all vehicles with emissions under 50 g CO_2/km qualify for a rebate of about $6000 [6], while in France any vehicle with CO_2-emissions under 20 g/km may receive a rebate of $9400. This rebate is reduced to the Swedish level when the CO_2-emissions are between 50 and 60 g/km [7]. In the UK the subsidy is flat as long as a minimum range limit is met (16 km for PHEV) [8]. The most generous subsidies are in Norway and Denmark where PHEVs and BEVs are exempted from the high registration taxes that more than double the price of conventional vehicles [9,10].

2 Methodology

As a basis for the analysis, we compare three different objective functions to find a fleet-optimized size of the PHEV battery under different techno-economic conditions; the maximization of the

- TCO savings in the car fleet, TCO_{OPT},
- electric drive fraction of the car fleet, EDF_{OPT},
- number of PHEVs in the car fleet, $PHEV_{OPT}$.

It is assumed that regardless of objective function, the car owner chooses a PHEV when economically viable, that is, when it has lower TCO than the corresponding HEV. We thus assume that the consumer's choice is only affected by the direct economics involved in buying and driving the car. In the case of $PHEV_{OPT}$ there are situations when two or more battery sizes result in the maximum (and same) amount of PHEVs in the fleet. The smallest battery size will then be chosen.

For the evaluation a simple techno-economic model of the car is combined with GPS-logged individual movement patterns for 445 privately driven Swedish cars. Fleet cars are thus excluded; although these can very well be the most suitable to electrify initially, they represent a minor share of the total car fleet. The cars consist of both privately owned and privately driven company (fringe benefit) cars. They are derived from positive answers to a request for participation sent to a random selection of owners/drivers. The cars are not older than about 9 years and come from a region containing about one sixth of all Swedish cars. The driving should therefore be reasonably representative for Swedish movement patterns among cars. (The data set for movement patterns has been previously described, when not fully completed though, in [11] and is also presented in parallel at this conference [12]). We assume a so called charge depleting/charge sustaining mode (CD/CS-mode) for the PHEV, that is, the car is first driven on electricity only and when the battery reaches its lowest allowed state of charge (SOC), it will sustain the long term SOC and functions as a hybrid until next recharging. The yearly distance driven on electricity is estimated for each individual car from its movement pattern, assuming a specific recharging pattern. The battery is assumed to be fully charged when recharged.

The vehicle costs involved in the techno-economic model are an annuity of the investment cost, and the yearly fuel and electricity costs. All other costs, such as maintenance costs, are assumed equal for different cars and will therefore not affect the choice of vehicles. The basic idea is then that compared to an HEV, a PHEV should be economically viable when the initial extra investment costs for the PHEV are paid for by the lower energy costs made possible by driving on grid electricity. The cost savings [$/km AER, yr] from a marginal increase in battery size will depend on the resulting yearly extra km of electric driving and the savings per km from using electricity instead of fuel.

$$marginal\ savings_i = d_{e,i}(AER) * (p_f e_f - p_e e_e)$$

Here $d_{e,i}$ is the annual marginal distance [km distance yr^{-1}/km AER] driven with electricity at a certain all electric range (AER) for vehicle i, p_f and p_e are the fuel and electricity prices [$/kWh], respectively, and e_e and e_f are the specific use of electricity and fuel [kWh/km], respectively.

The marginal cost for battery range depends on the cost c for marginal battery capacity [$/kWh (nominal)], the annuity α [yr^{-1}], the utilised share β of the battery [kWh (utilized)/kWh (nominal)], and the specific electricity use e_e

$$marginal\ cost = \alpha\beta^{-1}ce_e$$

Besides the cost for the additional battery capacity, the yearly extra costs consist of an annualized initial investment cost αC_{fix} [\$/yr] for turning an HEV into a PHEV corresponding to the extra non-battery equipment needed such as the charger and to any necessary or demanded increase in the power of the electric driveline, Fig 1. The TCO will be minimum when the marginal cost equals marginal savings, while the viability of the PHEV also needs to consider the added cost given by the investment C_{fix}. The maximum battery size considered is bounded to an upper AER of 200 km, though. A possible subsidy S at the purchase of the vehicle will also influence the viability.
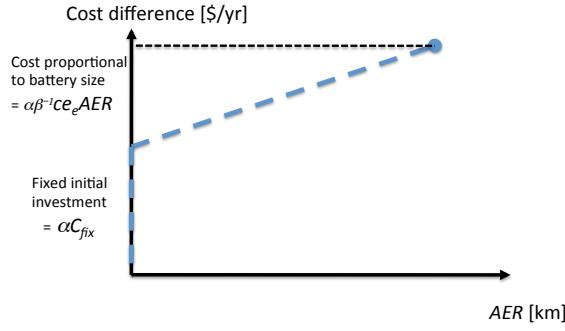

Figure 1: The assumed cost difference structure between an HEV and a PHEV. For parameters in the figure see the text.

Through this model we have analysed how different techno-economic conditions and battery sizes will influence the total life cycle cost and the share of driving done with electricity for the individual car owner. Aggregating these values gives information about the cumulative cost savings for car owners, share of electric driving and share of PHEVs in the car fleet.

Various techno-economic conditions are covered by changing the parameters. For transparency the initial cost C_{fix} and marginal battery cost c are varied, while the other parameters are kept fixed, Table 1. (Any assumed change in a parameter can easily be converted to a corresponding change in the specific battery cost, though. Also, the parameters are assumed the same for all car owners, i.e., there is no influence from such factors as the type, size or quality of the car, nor from any possible deviating cost situation for, for instance, company cars.) The fuel price corresponds roughly to the current situation in Europe with fuel prices around 1.5 Euro per litre of gasoline. The electricity price varies more

between countries in Europe and with time. Nighttime charging should possibly be cheaper than during the day. It is also ambiguous if any fixed tariffs for electricity should be included or not. The electricity price could thus be both larger and smaller than the fuel price. Here, the fuel prices are set equal due to this uncertainty and to focus on the difference in energy efficiency as a source for differences in cost per kilometre. The annuity of 0.15 corresponds to for instance an annuity loan over 8 years with an interest rate of 5%. This time period covers the most significant part of vehicle lifetime economics and could thus be a reasonable period for payback of an initial investment. The utilization share is in the range of current PHEVs, for which the depth of discharge (DOD) is limited for longevity of the battery.

Table 1: Assumed values of the techno-economic parameters.

Parameter	Value
Specific fuel use, e_f	0.45 kWh/km
Specific electricity use, e_e	0.15 kWh/km
Fuel price, p_f	0.2 \$/kWh
Electricity price, p_e	0.2 \$/kWh
Annuity, α	0.15 yr^{-1}
Utilization share, β	0.7

The recharging is assumed to take place after every break of at least 10h, which for most cars corresponds to charging once a day during the night, for those days when driving has taken place. As an alternative we also assume recharging after every break of at least 4h. This effectively singles out charging also at the workplaces. Figure 2 gives a histogram of average driving distances per charging period. The power requirement for the charging is moderate and is reasonable for household charging; for a 10h break even a range of 200 km requires at maximum an average charging power of 3 kW, which corresponds to less than 14 A at 220 V (single phase). Regular charging at workplaces can be assumed to require maximally less energy when daily commuting distances are normally limited in distance.

A subsidy S at the purchase of the vehicle can be a combination of a fixed amount and an amount proportional to the battery capacity. Thus a subsidy can alleviate the initial investment cost for the PHEV, by decreasing C_{fix} and/or the specific battery cost c.
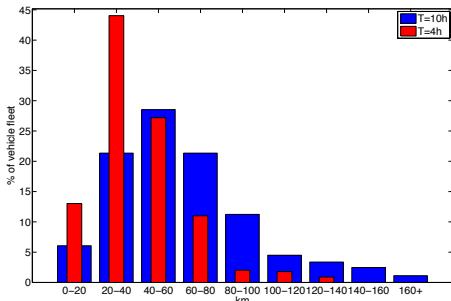
Figure 2: Average distance per charging period for the 445 cars in the data set. The blue (red) bars correspond to the scenario where the car is assumed to be fully recharged after a pause of at least 10h (4h).

3 Results

Figure 3 presents for low C_{fix} ($200) the results of optimizing according to the three objective functions, respectively, as a function of the marginal battery cost. The battery sizes are very small when battery costs are just enough, or around $800 per extra kWh, to achieve PHEV viability for some of the cars. The battery size for TCO_{OPT} and EDF_{OPT} will increase with lower battery cost although not in the same pace, while the $PHEV_{OPT}$ battery is small independently of the economic prerequisites for the battery. When the battery cost decreases, the objective to maximize the number of viable PHEVs always gives a small battery to meet the requirement of
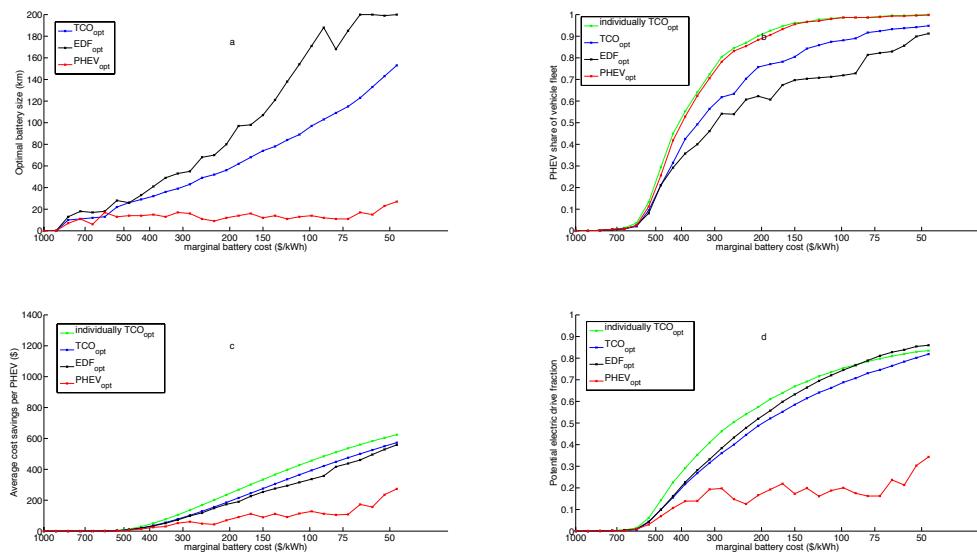
cars with less and less driving and incorporate them in the fleet of viable PHEVs.

Maximising the share of electric driving, EDF_{OPT} and maximising the cumulative cost savings, TCO_{OPT}, are closer in results compared to maximising the number of PHEVs, $PHEV_{OPT}$, which in general gives much lower electric drive fraction and users' TCO savings. The resulting fleet TCO savings, electric drive fraction, and number of PHEVs are, as expected, the biggest for respective objective function and also come close to the outcome for an individual optimisation of the batteries, which are also depicted in the Fig 3 for comparison.

Figure 4 gives the corresponding results when C_{fix} is high ($3500). Due to the high initial investment cost, the introduction of viable PHEVs is postponed until the marginal battery cost comes down to around 400 $/kWh. The viable and optimal batteries are now much larger corresponding to a range of 60 to 80 km to be able to accumulate enough driving on electricity to compensate for the initial investment. The optimal battery sizes differ less than for low C_{fix}. For TCO_{OPT} and EDF_{OPT} they are now almost equal but still $PHEV_{OPT}$ singles out and gives the smallest battery with a size almost independent of the battery cost. Since the optimal battery size is similar for the different objective functions, the spread in TCO, EDF and number of PHEVs is also smaller.
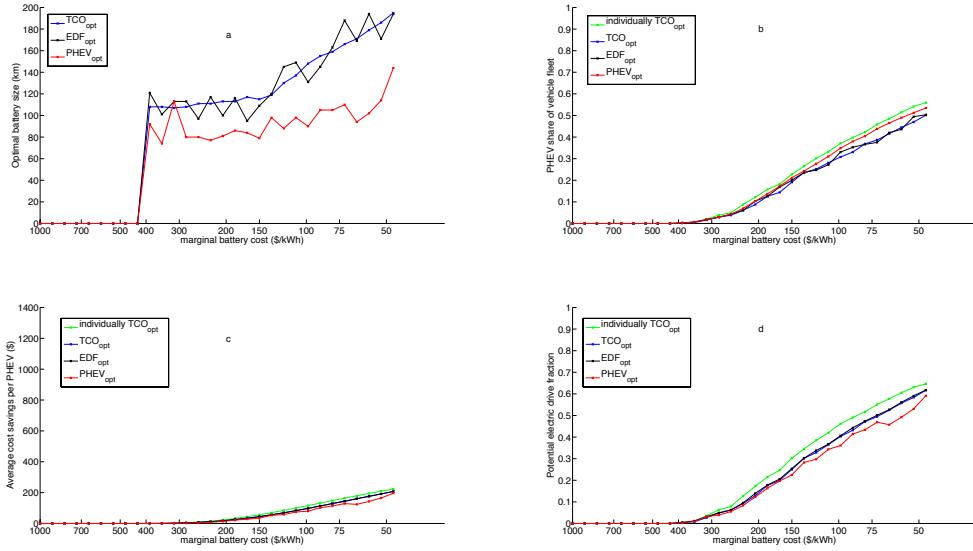

Figure 3: For the car fleet, when C_{fix} is low (= $200) and night-time charging only (T=10h), as a function of the marginal battery cost, a) the optimal battery size; b) the share of PHEVs; c) cost savings per car; d) the share of electric driving.

Figure 4: For the car fleet, when C_{fix} is high (= \$3500) and night-time charging only (T=10h), as a function of the marginal battery cost, a) the optimal battery size; b) the share of PHEVs; c) cost savings per car; d) the share of electric driving.

Figure 5: For the car fleet, when C_{fix} is low (= \$200), night-time charging only (T=10h), and a flat subsidy of \$5000, as a function of the marginal battery cost, a) the optimal battery size; b) the share of PHEVs; c) cost savings per car; d) the share of electric driving.
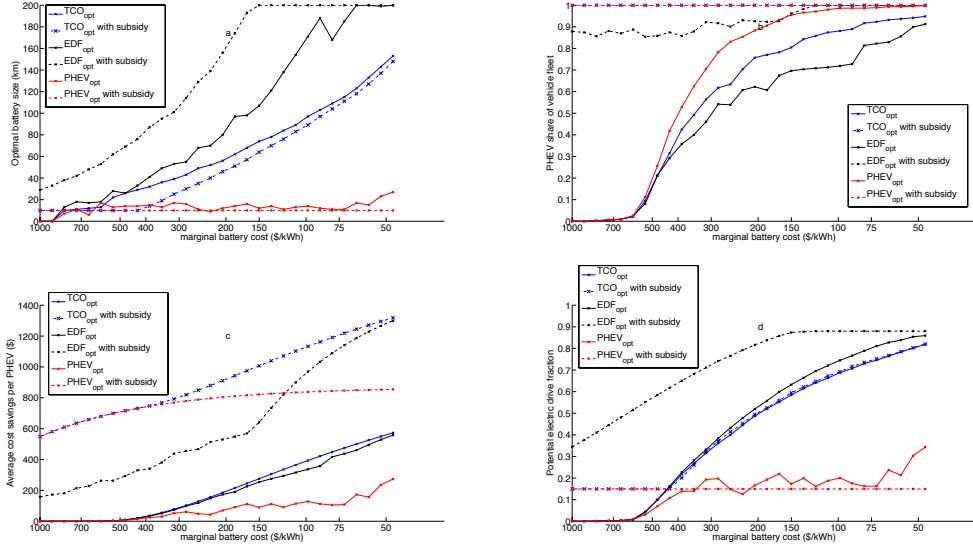
Compared to the case with a low C_{fix}, overall the share of PHEVs in the car fleet is greatly reduced. Also the electric drive fraction is reduced for TCO$_{OPT}$ and EDF$_{OPT}$, due to the lower number of cars, but not to the same extent as the PHEV share because of the large batteries.

Larger battery sizes, compared to the case with a low C_{fix}, imply that the EDF increases for lower battery costs for the PHEV$_{OPT}$ case. The TCO savings per car is reduced in all three cases because of the higher costs involved.
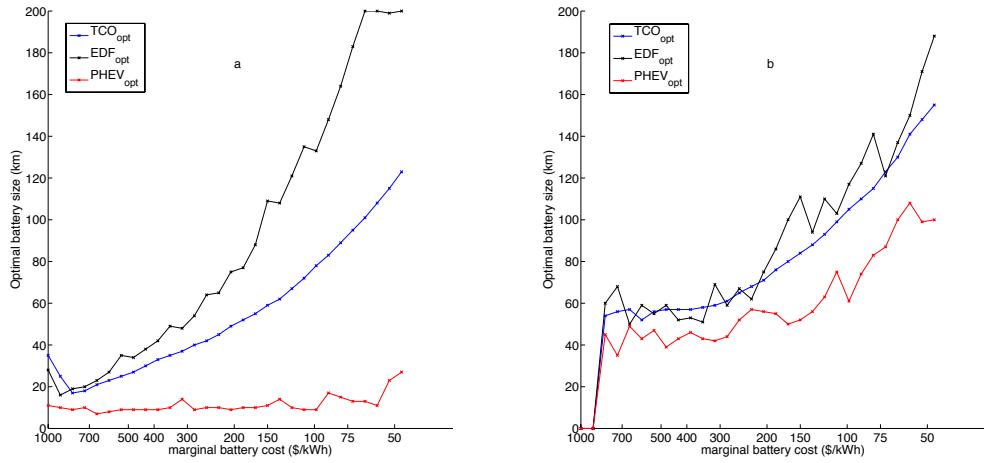
Figure 6: For the car fleet, as a function of the marginal battery cost, the optimal battery size, when charging also at workplaces (T=4h) and a) low C_{fix} (= \$200), and b) high C_{fix} (= \$3500).

The high C_{fix} can be alleviated by a fixed (battery-size independent) subsidy, to facilitate an earlier introduction of PHEVs. A precisely designed purchase rebate could turn the high C_{fix} scenario back into the scenario with low C_{fix} shown in Fig 1. If the subsidy is much greater than C_{fix} we get a situation as depicted in Fig 5. It shows the situation when a fixed subsidy of \$5000 is eligible for PHEVs with a battery of 10 km range or more. With a C_{fix} corresponding to \$3500 this means the subsidy brings the cost of the car, without battery, below a corresponding HEV. With such a subsidy all car owners in the fleet would benefit from buying a PHEV already at a marginal battery cost of 1000 \$/kWh. In the EDF$_{OPT}$ case the battery size increases with lower battery costs and the electric drive fraction follows. In the PHEV$_{OPT}$ case, independent of battery cost, all PHEVs with the minimal battery size required for the subsidy become cost efficient. There is thus a risk that the subsidy creates a minimum battery size that dominates the market. In the TCO$_{OPT}$ case the battery size stays at the same minimum level until a battery cost of about 450 \$/kWh. At higher battery costs only a minority of the drivers would benefit from a larger battery and their potential savings are thus dwarfed by the higher losses from the rest of the drivers that have invested in PHEVs. The total electric drive fraction increases in the TCO$_{OPT}$ and PHEV$_{OPT}$ cases until a battery cost of about 350 \$/kWh. Below this battery cost level, the subsidy has little or no effect on the electric drive fraction in the case of TCO$_{OPT}$ and the subsidy may even have a negative effect on

the total electric drive fraction when optimizing for the number of PHEVs.

A better charging infrastructure, for instance charging possibilities also at the workplaces, shortens the distance between recharging. In general this facilitates a higher utilisation rate of smaller batteries and lowers it for the marginal capacity of large batteries [1]. Figure 6 gives the effect of charging also at the workplaces with low and high C_{fix}, respectively. (As mentioned making it possible to charge at the workplace is emulated by allowing charging for pauses over 4h.) The possible higher utilization of smaller battery makes the PHEV more viable and in both cases the PHEVs are introduced at higher battery costs compared to home charging only cases (given in Figs 1 and 2). (In the case where C_{fix} is low a hump in battery size at higher battery costs occurs. This is an effect of the specific movement pattern of the very few cars that are viable as PHEVs at this stage. When a greater number of PHEVs are introduced the optimal battery size comes down again.) Also, compared to only home charging, the optimal battery sizes are in general somewhat smaller due to lower utilization of the marginal capacity of larger batteries, but contrary have a considerably higher utilisation rate of the total battery capacity. Thus overall, providing more charging opportunities results in an increase of both the share of PHEVs and the electric drive fraction.

4   Discussion

We will here shortly point to some potentially conflicting interest in a build-up of a PHEV fleet,

taking departure in our two exemplary alternative cost structures of the transition to PHEV and in the corresponding results of what an appropriate battery size may be. These results may be considered for instance when formulating and evaluating policies meant to facilitate the introduction of electrified vehicles.

There is, as pointed to in Section 1, an uncertainty or spread in the possible transition and its cost when going from a fuel efficient 100% fuel-propelled vehicle to a PHEV, both when it comes to customers' expectation/demand and manufacturers' actual model output.

A market where PHEVs are perceived as requiring high C_{fix} to fulfil customers' performance demands or are realized only with high initial costs will require large PHEV batteries to be economically viable compared to the alternative. Behind less cost sensitive early adopters this will probably lead to a delay in the uptake of PHEVs, counteracting any possible societal goal of achieving a fast transition to electromobility.

Subsidies can be used to overcome a high C_{fix}, and bring a larger number of PHEVs to the market. To the extent the high C_{fix} results from customer expectation on performance rather than an absolute production cost difference it can be seen as a conflict between interests at the customer and societal level. Policies targeting customer expectation of the PHEV can possibly moderate this conflict.

In case of a low C_{fix} situation on the market, the results show that a high share of viable PHEVs in the vehicle fleet not necessarily results in a high electric drive fraction. This is interesting from a societal perspective if large benefits in greenhouse gas reductions and energy security are hoped for by an introduction of PHEVs to the market. Although the introduction could be done by a small battery an increase in size when battery prices decreases is necessary to achieve higher EDF and fuel substitution. It is thus of importance to see to that a transition to larger batteries is not delayed.

The probability for the "negative" outcome with continued small batteries could increase if car producers' interest is to sell a PHEV that suits the driving of as many people as possible which then should have a rather small battery. The case of PHEV$_{OPT}$ stood out from the other two with its in general smaller battery size, lower electric drive fraction and lower level of cost savings for the car owner.

CO_2 emission or fuel efficiency regulation rewarding specifically only the number of PHEVs sold may further enhance such a tendency as well. Introducing a flat subsidy independent of the battery size with the intention to alleviate an assumed high transition cost, that is, a high C_{fix}, can possibly worsen the situation. As our result shows there is a risk that a flat subsidy pushes the development towards smaller batteries, which is less optimal both for the drivers, with lower cost savings, and for society, with lower EDF. Instead PHEV subsidies in proportion to the battery-size-only would probably be more appropriate in case of a market with low C_{fix}.

Support to infrastructure investment to increase recharging option, for instance at workplaces, can be an important and efficient complement to subsidies directed towards the vehicle. Through better utilization of smaller batteries, and thus increased possibilities for the PHEV owner to achieve cost saving, this effectively works as a lowering of a high C_{fix} and enables an earlier introduction of PHEVs at a higher battery cost, a higher share of car fleet being PHEVs and a higher total electric drive fraction for the car fleet. The drawback discussed above for the low C_{fix} - high subsidy case is also avoided.

We have here analysed the introduction of PHEVs and argued on the supposition that there is one optimal battery and that the market is more or less homogenous. Neither needs to be true. It can be reasonable to assume that there are several optimal batteries and that different manufacturers will address different niches of the market and so on. We have done this both for simplicity and clarity of the arguments when pointing to potential conflicts in interest between various goals and actors. If not for anything else we need to be aware that there can be conflicting goals and that different policies may favour various actors differently depending on such things as cost structure and market expectations.

The short-term policy objective may differ from the medium and long-term, due to changes in technology and societal prerequisites over time. For instance, initially, as long as the carbon intensity of the electricity production is high, the policy could be tailored to support PHEVs and the number of cars, facilitating the build up of industrial capacity. Only later when more low-carbon renewable electricity is available, the objective could turn to maximizing the driving on electricity, facilitating climate mitigation. It may be desirable to increase the number of PHEV at an early stage when the technology is immature to

enhance technological development and cost reductions in order to maximize the electric drive range in the long run. In this case there could be less of an interest conflict between different actors.

5   Conclusion

We conclude that, in the vehicle design and when formulating policies for the introduction of PHEVs, it is important to consider the various aspects treated here, the driving patterns, the cost structure and the market for the PHEV and their interaction with different actors' possibly conflicting objectives and interests.

Acknowledgments

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Authors

M. Sc. Lars-Henrik Kullingsjö

Lars-Henrik Kullingsjö achieved a M. Sc. in Industrial Ecology in 2011 and is currently doing a PhD in System analytical modeling and assessment of design, viability and potential of plug-in hybrids at the Department of Energy and Environment, Chalmers University of Technology, Sweden.

Dr. Sten Karlsson

Sten Karlsson received a PhD in 1990 and is senior lecturer at the Department of Energy and Environment, Chalmers University of Technology, Sweden. His current research is focusing on energy efficiency and technology assessment, especially concerning private cars and the electrification of vehicles.

Dr. Frances Sprei

Frances Sprei is an Assistant Professor in Sustainable Mobility at the Department of Energy and Environment, Chalmers University of Technology, Sweden. Her research assesses different innovative personal mobility choices. She received her PhD in 2010 and has been a visiting scholar/post-doc at Stanford University.