Plug-ins – a viable efficiency option?

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Keywords
car transportation, plug-in hybrid electric vehicles, cost-efficiency, energy savings, CO_2 emissions, Sweden

Abstract
Transportation accounts for around one third of CO_2 emissions in Sweden. Personal cars in Sweden have one of the highest specific fuel uses in Europe. Mitigation strategies involve mandatory biofuel shares together with high taxation on gasoline and diesel fuels. From the current situation, one possible step to further increase car fuel efficiency is adoption of hybrid drivelines, which could be especially interesting with high pump prices. Furthermore Swedish electricity share is highly carbon neutral, therefore it could be desirable to use electricity from the grid to power personal vehicles.

Here we investigate under what circumstances plug-in extensions of hybrid electric vehicles with different all-electric range are cost-effective options for energy and fuel savings. The result is dependent on vehicle specification and applied cost methods. It is shown that a plug-in designed with a reasonably small all-electric range (30-40 km) for a wide range of circumstances could become an economically viable option in comparison to conventional and hybrid vehicles.

Introduction
Climate change mainly caused by anthropogenic CO_2emissions is by many perceived as the 21st century's greatest environmental challenge. Also the dependency of dwindling resources of oil calls for a future transition of the energy system. The personal transportation by car, today almost totally dependent on oil, is steadily increasing in volume and stands for a large share of CO_2 emissions and "oil dependence" in Europe and other industrialized regions. In many industrialised countries, the share of transportation in the total energy use is also increasing. Within the EU, transportation to the year 2020 is expected to contribute more than 60 % of the increase in CO_2 emissions (EC 2007).

In Sweden transportation accounted for about 36% the total emissions of CO_2 in year 2003 (calculated from Swedish Energy Agency 2005a). The personal vehicle system is dominated by internal combustion engine (ICE) cars. New personal cars in Sweden have the highest specific emissions of CO_2 in the European Union (Vägverket 2004). This is due to a vehicle fleet with large cars (Sprei and Karlsson 2007). Compared to most of Europe, Sweden has a low share of diesel cars due to non-favourable taxes for diesel cars motivated by exhaust emissions of hazardous substances. The number of cars as well as the annual driving distances have been growing and these trends are expected to continue (Vägverket 2003).

Significant reduction of CO_2 emissions from car transportation requires increased vehicle efficiency and/or changes to energy sources with less specific CO_2 emissions. In Sweden, mitigation strategies involve mandatory biofuel shares together with high taxation on gasoline and diesel fuels. Besides, demand for green cars is pushed by discounts on taxes and parking fees. Sweden is also part of the EU agreement with the car industry demanding voluntary improvements in efficiency for most car brands sold in the EU.

Drive train technology options today are conventional vehicles (CV) and electric vehicles (EV), although the last group is very small. (A glossary in the end of the paper also presents used abbreviations.) EVs, although very energy efficient in the use phase compared to CVs have achieved little market acceptance, mainly due to high costs for the storage batteries and low driving range between recharging. Other recent new options are hybrid (electric) vehicles (HEV), like the Toyota Prius, of which to date have been sold more than half a million vehicles worldwide. Hybrid vehicles provide a significant increase in efficiency by making possible a more efficient load regime of the engine, avoidance of idling, and recovery of at least some of the braking energy. Hybrid technologies have a higher capital cost than comparable conventional cars due to the extra electric and control equipment necessary while still keeping the engine, although possibly a somewhat downsized one. HEV cost is an important issue, and, for instance, although considerable cost reduction has been achieved, lower driveline cost has highest priority in further development of the Prius (Fujii 2006).

Recently, a new option is being considered: plug-in hybrid (electric) vehicles (PHEV) or just plug-ins. These are vehicles that can work as normal HEVs, but also as electric vehicles for a limited all-electric range or in blended operation using electricity from the grid stored onboard in a battery. A large share of the daily driving of cars is on shorter distances, for instance in Sweden 50 % of the total driving distance is in daily trips less than 35 kms (SIKA 2006). Thus, with battery for only a small range, say 20 to 50 km, with a plug-in using daily recharging, a considerable part of the driving can be operated in the all-electric mode. And this efficient electric mode would save considerable amounts of energy on the vehicle level and also driving costs if consumer prices of fuels and electricity are comparable on an energy basis. Compared to the pure HEV, the small extra battery capacity needed is possibly more than compensated for by the energy cost savings. Thus, given an HEV there could from a consumer economic point of view be good reasons to go one step further and aim for a PHEV. Of course, for further extension of the battery capacity, the marginally added possible use of grid electricity will decrease. Eventually, with a very large all electric range, the engine is not necessary, and you have an electric car, though. But are there reasons to believe that the savings of energy and avoidance of the engine are not fully compensating the costs of the much larger batteries needed? Are thus the economics such that neither the HEV nor the EV are the optimum but something in between, i.e., the PHEV?

A similar question has been raised for the CV – HEV continuum: Have neither the CV nor the (full) HEV the lowest costs but something in between, a so called mild hybrid, which with a small and considerably cheaper electric motor/generator reaps the low-hanging fruits and most of the fuel savings achievable with the full HEV? Several European car manufacturers have been sceptical about the HEVs and argued for, if anything, such mild hybrids. And in a recent big joint European well-to-wheel study on CO_2-emissions savings of different possible 2010+ drivelines, it was also concluded from the detailed modelling efforts that fuel savings from hybridization beyond a relatively small electric motor quickly levelled out (CONCAWE/EUCAR/JRC 2006).

There are currently no commercial PHEVs produced by car manufacturers. Some small firms offer packages for fitting to available HEVs, like the Toyota Prius, to a considerable cost, though. A barrier today for PHEVs as for the EVs, are the batteries. Some recent US studies have investigated the potential for plug-ins both from a technical and economic point of view (EPRI 2001, EPRI 2004, Markel and Simpson 2006, Kliesch and Langer 2006). These studies evaluate various options under US conditions. In Europe considerably higher pump prices are prevailing, which could increase the viability of plug-in hybrid vehicles compared to conventional and hybrid vehicles using more fuel.

The main objective of this study is to investigate if PHEVs could become a viable option under European conditions. Especially we want to investigate our hypothesis that a PHEV is a better option than the HEV. We will investigate the viability from a car ownership economic point of view. The study focuses on Sweden, which compared to the US, has considerably higher pump prices, but also shorter driving distances.

Methodology

To determine whether PHEVs are a viable option, we compare the private costs of buying and driving a PHEV with the costs of having a CV or a HEV. Three PHEVs with different all-electric ranges (AER, i.e., the maximum range on battery only), 32 km, 64 km, and 96 km are investigated. EVs with different ranges are also considered for comparison. (The respective range is denoted in miles, though, e.g., the 32 km range vehicle is denoted PHEV 20.) The costs included in the comparison are vehicle capital costs and driving energy costs.

For each vehicle, we define two sets (the EPRI case and the NREL case) of vehicle specifications, cost functions, and retail price calculation method. These depart from two sets of resources: one is results from studies performed by the Electric Power Research Institute (EPRI) (EPRI 2001), the other is results from modelling efforts and analyses performed by the National Renewable Energy Laboratory (NREL) (Simpson 2006). Vehicle components sizing together with cost functions are used to estimate the cost of individual components, then the vehicle retail price is determined with help of mark-ups for accounting assembly costs and manufacturer and dealer profits. The derived vehicle retail price is annualized to give the owner's vehicle capital costs.

For EPRI vehicle specifications which are based on all-electric operation, (i.e., only the electric motor drives the car during the battery charge depleting mode), the energy use is divided into the annual electricity use and gasoline use. The annual electricity driving fraction is estimated by using Swedish daily driving patterns (SIKA 2006). For NREL vehicle specifications which are based on blended operation, (i.e., the engine and the electric motor in parallel drive the car also during the battery charge depleting mode), the consumption of electricity and gasoline per km are used. For both cases Swedish energy carrier prices are then used to calculate the driving energy costs. The comparison of the vehicles is performed on the basis of total costs per driven kilometer and the sensitivy of the result to crucial parameters is investigated.

VEHICLE SPECIFICATIONS

In Tables 1 and 2 vehicle specifications for the two sets are shown. It should be noted that EPRI and NREL vehicles with the same denomination are different. The NREL vehicles have higher performance targets than the EPRI ones. NREL vehicles utilise blended operation with a lower limit for engine size of

Table 1. EPRI vehicle specifications.

Vehicle	CV	HEV 0	PHEV 20	PHEV 40[b]	PHEV 60
curb mass [kg]	1499	1500	1558	1622	1708
engine power [kW]	127	67	61	49.5	38
motor power [kW]	0	44.3	51.3	63	74.7
total power [kW]	127	111.3	112.3	112.5	112.7
power to mass ratio [W/kg]	84.7	74.2	72.1	69.3	65.9
DOH (motor power/total power)	0%	40%	46%	56%	66%
battery energy [kWh]		3.63	7.35	14.8	22.42
Battery power/energy (P/E) ratio [1/h]		13.47	7.35	5.16	4.41
Depth of discharge (DOD)[a]		80%	80%	80%	80%
All-electric range (AER) [km]	0	0	32	64	96
Electric only efficiency city [Wh/km]			200	203.4	206.8
Electric only efficiency Hwy [Wh/km]			226.2	228.7	231.2
Fuel only efficiency city [l/100km]	11.3	6.4	6.4	6.30	6.1
Fuel only efficiency Hwy [l/100km]	7.3	6.9	6.4	6.25	6.1

[a] DOD, i.e., the allowed discharge fraction, has been adjusted to 80%, assuming that the original was 100 %.
[b] Own estimates. The main specifications have been obtained by interpolating PHEV 20 and PHEV 60 (motor power, total power, battery energy, and energy efficiencies).

Table 2. NREL vehicle specifications.

Vehicle	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60
curb mass [kg]	1429	1412	1531	1598	1636
engine power [kW]	122	77	81	83	84
motor power [kW]		36	43	45	46
total power [kW]	122	113	124	128	130
power to mass ratio [W/kg]	85.4	80.0	81.0	80.1	79.5
DOH (motor power/total power)	0%	32%	35%	35%	35%
battery energy [kWh]		1.5	11.8	19	23.6
Battery power/energy (P/E) ratio [1/h]		32.80	4.90	3.2	2.60
State of charge (SOC) window		37%	47%	59%	73%
Electricity consumption [Wh/km]			58	96	120
Fuel consumption [l/100km]	10.3	7.4	5.7	4.5	3.7

80 kW (Simpson 2006). The EPRI approach is different with the PHEVs using all-electric operation and some trade-offs between performance and cost have been performed, while having a reasonably similar performance to the base CV (EPRI 2001).

In the EPRI specifications, when the battery size increases, the total power decreases and the degree of hybridisation (DOH, i.e., the motor to total power ratio) increases. In the NREL specifications when the battery size increases, the total power increases and the DOH increases, however DOH is limited to 35 %. NREL has significantly bigger batteries for the same plug-in denomination because of the state of charge (SOC, i.e., the remanining fraction of the battery capacity) window. NREL has a goal of 15 years of battery lifetime (Simpson 2006). As the lifetime goal increases, SOC decreases. Batteries are the most important cost difference relative to CV vehicles. Considering the power to mass ratio of vehicles, it can be observed that in EPRI vehicle specifications (Table 1), the power to mass ratio decreases significantly as DOH increases, while in the NREL specifications (Table 2), power to mass ratio is practically kept constant and at a considerably higher level than every EPRI hybrid options. Power to mass ratio is an important indicator of performance. A higher power to mass ratio with similar aerodynamics implies a higher performance.

The electric vehicles are specified in a different way, Table 3. It is assumed that a power to mass ratio of 60 W/kg is enough for a totally electric vehicle. Battery capacity is based on the same relation for all-electric range to battery energy as for the PHEV 60 (0.6 km/kWh) based on EPRI (2001). The ratio of motor power to battery power is set to 0.7 for all the EVs. Assuming the same battery technology used for the PHEVs (NiMH), the EV efficiency (kWh/km) is estimated using a function which relates the electric-only efficiencies of the EPRI plug-in options to their masses. Li-ion battery technology would imply lower total mass and higher efficiency, though.

Table 3. Electric vehicles specifications.

Vehicle	EV 60	EV 350	EV *[a]
curb mass [kg]	1729	3130	1708
motor power [kW]	103.79	187.83	102.5
total power [kW]	103.79	187.83	102.5
power to mass ratio [W/kg]	60.00	60.00	60.00
DOH (motor power/total power)	100%	100%	100%
battery energy [kWh]	22.4	130.8	20.1
P/E ratio [1/h]	6.61	2.05	7.12
Depth of discharge (DOD)	80%	80%	80%
all-electric range (AER) [km]	96	520	88
Electric only efficiency city [Wh/km]	201.8	265.3	200.8
Electric only efficiency Hwy [Wh/km]	227.5	273.7	226.9

[a] The battery capacity for the EV* is the calculated for an EV that has the same total costs/km as the CV i our estimates (for comparison).

CAPITAL COSTS

Combining specified component sizes and cost functions, the costs of individual components are calculated. Cost functions are based on EPRI (2001). The cost functions are long-term expectations with technological advances expected for 2010 and when producing 100 000 units per year (EPRI 2001).

There are also non-variable costs, which do not vary among the vehicle drivetrain options (or at least not continuously). The most important non-variable cost is that of the glider, i.e., the car except the driveline. All cases are based on a midsize sedan. The glider for EPRI Base Method including mark-ups has a price of around 12 470 USD, while in the EPRI ANL Method the price is around 11 520 USD (EPRI 2001). The NREL price for the midsize sedan glider is 17 390 USD (including mark-ups) (Simpson 2006). For EPRI the transmission component cost is 1 045 USD in the CV and 625 USD in the hybrid options (EPRI 2001).

There has been used three different methods for estimating vehicle retail prices. The first method is called the Base Method (cited in EPRI 2001), and it is based on the cost of manufacturing, manufacturing overhead, warranty costs, manufacturing profits and dealer overhead and profits. This method describes a situation where all the components are manufactured by the original manufacturer; mark-up factors are 1.5 and 1.16 for the manufacturer and dealer respectively (EPRI 2001). The second method is called the ANL Method (cited in EPRI 2001), and it describes a situation where the electric components are supplied by outside suppliers, the mark-up factor for electric components is 1.5. Manufacturing and dealer mark-ups are combined into a single one and put to 2.0 (EPRI 2001). Battery mark-ups are treated differently in the two EPRI methods. Battery mark-ups are defined as constant additions instead of factors, 800, 850 and 900 USD for the HEV 0, PHEV 20 and PHEV 60 respectively (EPRI 2001). Here as base case for EPRI vehicle specifications, the average of results from the Base and the ANL methods is used. The third way of calculating the price is using the costs without considering separately the batteries. Mark-ups for manufacturer and dealer are applied directly. This way of calculating provides concordance with NREL prices. The mark-up factors are 1.5 and 1.16 for the manufacturer and dealer respectively (Simpson 2006 based on EPRI 2001). Here we call it the NREL method.

Comparing the EPRI methods only, the Base method would result in higher prices than the ANL Method. The NREL method results in the highest prices of them all. In the NREL method battery mark-ups are treated like every other component. This is very significant because, while in the EPRI method the part of the price that accounts for the battery does not vary significantly with the battery size at long AERs, in the NREL method it varies proportionally with the size. This implies a higher final price for the same battery capacity with NREL method compared to EPRI (at reasonably big battery sizes). Also, NREL PHEV specifications with the same denomination as EPRI ones have higher battery capacities (see Tables 1 and 2). The use of NREL cost method and NREL specifications would result in significantly higher vehicle prices than EPRI specifications with EPRI price methods for the same PHEV denomination. The battery is the most important part of the incremental difference in capital cost of PHEVs. The situation for the HEVs is different, since NREL method applied to small battery capacities results in a low battery final price and the NREL specifications also have a small battery capacity.

The retail price is then annualized. (We use an annuity factor of 0.1295 corresponding to 10 years and 6 % discount rate, which is a commonly used social discount rate in energy capital cost estimates.) The cost per year is divided by the annual driving distance for obtaining the capital cost per km. In the calculations the used currency conversion is 8.3 SEK/USD, which is equal to the average exchange rate in the 10-year period Dec. 1996 to Nov. 2006 (http://www.x-rates.com/d/SEK/USD/hist2006.html).

DRIVING ENERGY COSTS

EPRI vehicle specifications

A driving distance of 16 000 km per vehicle and year is used, which is a linear extrapolation to 2015 of the trend from 1999 through 2004 (SIKA 2005). For calculating the driving energy cost of PHEVs for the EPRI specifications, first the electric driving distance per year has to be defined. The cumulative daily driving distance by cars in Sweden is shown in Figure 1. Assuming all cars as PHEVs with a specific AER, in theory, all daily trips less than the AER could be totally powered by electricity. Of the trips longer than AER a fraction (i.e. AER/trip distance) could run on electricity. However, the possible share of electricity will in the single case be strongly dependent on the specific driving pattern for that car, which can be far away from the average trip distribution pattern revealed by the statistics. Important factors are number of days driving and total driving distance, annually. The fraction of the annual driving distance that will be operated by electricity is called here the electric driving fraction (EDF). Table 4 gives some simple illustrative examples, for which the maximum possible EDFs vary between 5 and 100 % assuming one nightly recharging.

We use rather conservative estimates a base case for the EDFs of the PHEVs. Each EDF is set equal to the cumulative share of average driving distances per day per car in Sweden up to the corresponding AER, Fig 1 and Table 5. This assumption on EDFs corresponds to that each of the investigated PHEVs has a driving pattern according to the average statistics, Fig 1, and that recharging is done once during nights and that daily driving distances equal to and lower than the AER are run totally on electricity, and all longer trips are100 % powered by the engine. (For a vehicle with this driving pattern the maximum possible EDF is larger due to the fact that also daily trips longer than the AER can partly be powered from the grid. The EDF is further dicussed in the sensitivity analysis.) The fuel driving distance is the total annual driving distance minus the all-electric driving distance. The total cost of electricity and fuel for the year are calculated using the electric only efficiencies and fuel only efficiencies defined by EPRI (EPRI 2001). Different efficiencies for highway driving and urban driving are taken into account. For comparison the mileage weighted probability (MWP) for US driving distances for low, average and high driving commute distance is also presented in Table 5. Differences between operation efficiencies in highway and city driving are taken into account. The ratio of highway driving to the total driving distance in low-commute driving households in the US is 0.53 (derived from EPRI 2001) and is used as valid for Sweden.

Table 4. Maximum possible electric driving fraction with one nightly recharging for different driving pattern parameters and AER.

AER	Annual driving distance (km)	Number of days driving annually	Maximum electric driving (km)	Maximum electric driving fraction (%)
32 km (PHEV 20)	16000	50	1600	10
		200	6400	40
		365	11680	73
	32000	50	1600	5
		200	6400	20
		365	11680	37
64 km (PHEV 40)	16000	50	3200	20
		200	12800	80
		365	16000	100
	32000	50	3200	10
		200	12800	40
		365	23360	73

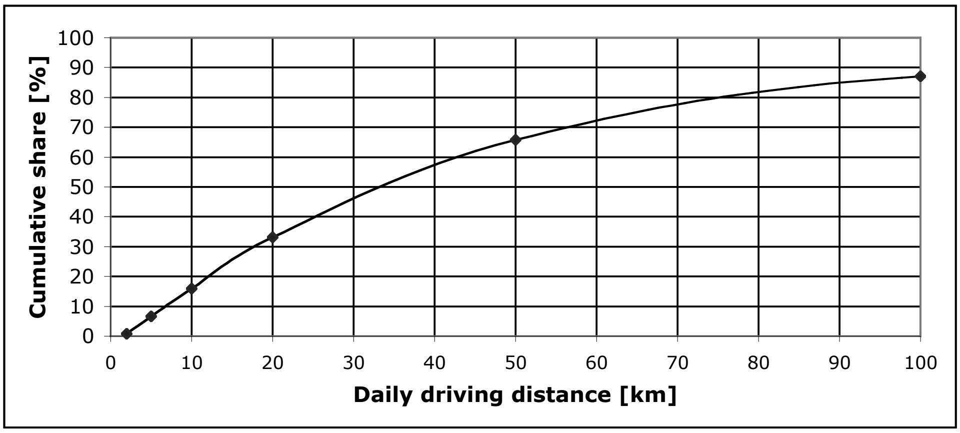

Figure 1. Cumulative share of average driving distance per day per car. Data for Swedish average 1999 to 2001 (adapted from SIKA.(2006))

Table 5. Assumed electric driving fraction (EDF).

Vehicle Options	AER [km]	Assumed EDF[a]	US low commute distance MWP[b]	US average commute distance MWP[c]	US high commute distance MWP[d]
PHEV 20	32	0.48[e]	0.64	0.40	0.30
PHEV 40	64	0.74		0.60	
PHEV 60	96	0.86	0.76	0.74	0.72

[a] EDF is set equal to share of cumulative average driving distance per day per car up to the AER (from Figure 1)
[b, c, d] The mileage weighted probability (MWP) for US has been obtained from EPRI (2001).
[e] For comparison, the average maximum possible EDF from data presented in Figure 1 is around 0.7.

NREL vehicle specifications

For calculating the energy cost for NREL specifications, the fuel and electricity consumption per km are used for the total driving distance in the year. Prices of energy carriers for Sweden are used in the calculation for both cases.

The blended operation is based on NREL specifications (Table 2). Apparently the control strategy will basically tend to use the battery-motor combination at the limits, and use the engine as a supplement (Simpson 2006). It is assumed that the fuel consumption and the electricity consumption occur at the same time. However, after the battery capacity is used, the vehicle would have to be driven in a fuel-only mode. But this will happen only when the vehicle exceeds 100 km and is thus not very significant (Fig 1.), and has been disregarded here.

Table 6 presents the base case energy carrier prices used for energy cost calculations.

TOTAL COSTS AND SAVINGS

The total cost per km here considers only capital and energy costs, that is, other costs like maintenance and insurance are not considered, nor are any possible environmental policy incentives taken into account, (if not already included in the energy prices such as the Swedish CO_2 tax). To find the optimal options for different conditions, a spreadsheet model in which conditions can be easily varied is used. The main results are calculated as savings of each vehicle option compared to CV in a total cost per km basis.

Table 6. Energy carrier prices in Sweden 2004

Energy Carrier	Price (including tax)	Tax
Sweden Gasoline[a] [SEK/l]	10.09	6.83
Sweden Domestic Electricity[b] [SEK/kWh]	1.22	0.48

[a] Svenska Petroleum Institutet 2006

[b] Swedish Energy Agency 2005

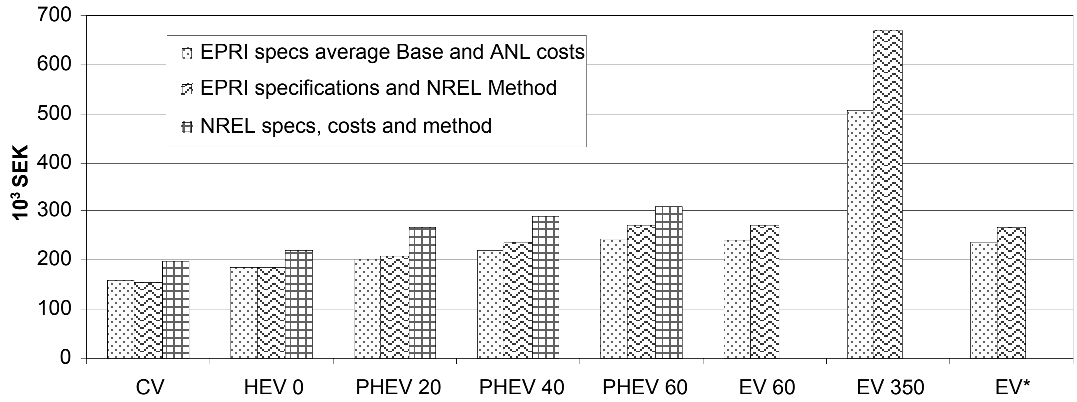

Figure 2. Capital costs of the different vehicle options.

Results

CAPITAL COSTS

Figure 2 gives the capital costs for the 8 vehicle options with the different applied specifications and cost methods. The EPRI specifications options share the same glider price. The NREL options share a glider with a higher price. The option with the lowest cost is the CV. The hybrid options have higher prices, the larger the battery capacity and AER. Also for the three EVs, the longer the range, the higher the cost, due to larger battery and more powerful motor with weight. The EV 60 and EV * have prices reasonably comparable to the PHEV 60 price. In fact the EV 60 and PHEV 60 have the same battery capacity; the main difference is that the EV 60 does not have engine traction. The prices of the two options are similar because the motor of the EV 60 is bigger, which partially compensates for the engine cost of the PHEV 60.

It is important to notice the difference in prices achieved by the various specification and cost methods. For the same EPRI-specified vehicle, compared to the EPRI average cost method, the NREL cost method gives a lower cost for the CV, but the cost increases much faster with larger AER due to the differences in mark-ups (explained earlier). The vehicles according to NREL specifications have a significantly higher price, mainly due to the cost method and a higher glider price. At larger AERs higher battery capacity also becomes important.

The differences in costs for achieving plug-in capacity are considerable. Table 7 shows the cost difference of the PHEV 20 relative to CV and HEV 0 for the various specifications and cost methods. The incremental difference of the PHEV 20 to the CV for NREL specifications with NREL method is around 50 % higher than that with EPRI specifications and EPRI method. Furthermore, the incremental cost for going from an HEV 0 to a PHEV 20 is significantly higher (almost 3 times) with NREL specifications and method than with the ones of EPRI. With EPRI method, a higher share of the price difference depends on the components. As mentioned, with equal PHEV specifications, retail price calculated using the EPRI method will be lower than the price obtained by the NREL method.

DRIVING ENERGY COSTS

Figure 3 shows the specific cost of driving energy of all the vehicle options. The energy cost of the CVs is the highest. It decreases with DOH/AER, due to the increased use of more energy efficient electric traction and the roughly comparable prices on electricity and gasoline on an energy basis in Sweden.

Table 7. Retail price difference of PHEV 20 to CV and HEV for different vehicle specifications and cost methods [10^3 SEK].

Specification and cost method	Price difference PHEV 20 – CV			Price difference PHEV 20 – HEV 0		
	Total	Components	Mark-ups	Total	Components	Mark-ups
EPRI specifications and EPRI average cost method	45.7	30.2	15.6	16.8	12.4	4.3
EPRI specifications and NREL cost method	52.5	30.2	22.3	21.6	12.4	9.2
NREL specifications and NREL cost method	69.2	39.8	29.4	45.3	26.0	11.1

Table 8. Savings in energy costs. PHEV 20 costs compared to CV and HEV costs.

Specification	PHEV 20 – CV [SEK/km]	PHEV 20 – HEV 0 [SEK/km]
EPRI specifications	0.46	0.21
NREL specifications	0.39	0.10

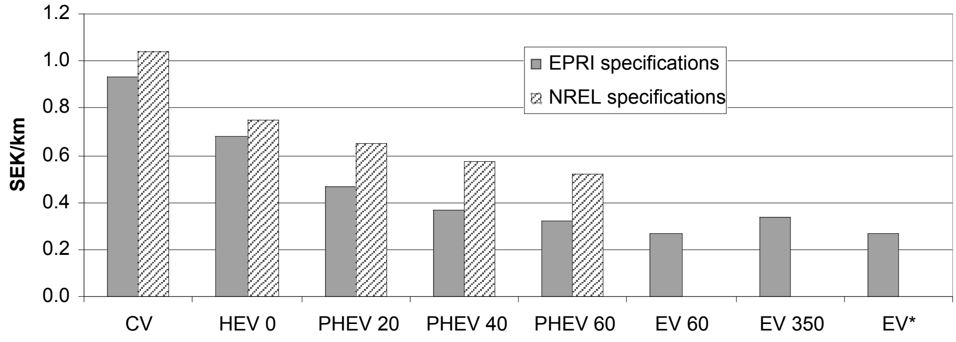

Figure 3. Driving energy costs with EPRI and NREL vehicle specifications.

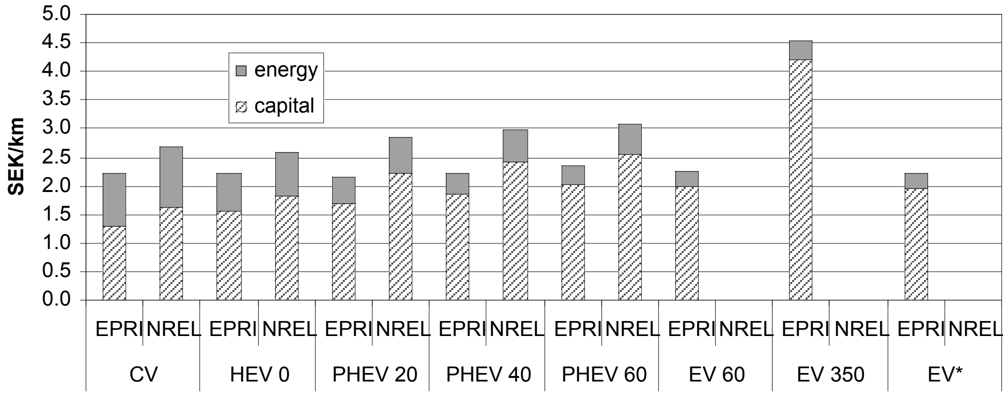

Figure 4. Total costs in SEK/km for vehicles with EPRI specifications and EPRI average cost method and with NREL specifications and NREL cost method, respectively.

The marginal benefit to increased AER decreases, though. The energy cost of the EV * is the lowest. The EV * has a range of 88 km (55 US miles) and since it does not have a "big" battery and it does not have an ICE, it is the lightest of the vehicles and has the highest efficiency. The energy cost is also related to performance: The vehicle with EPRI specifications has always a lower energy cost than the corresponding car with NREL specifications. Notably, the savings due to hybridization is larger for NREL vehicle, while the savings when increasing the DOH/AER is considerably less. Especially, going to PHEV 20 from HEV 0 saves almost only one third of the driving costs in the NREL case compared to the corresponding EPRI one. The difference in savings when changing from HEV 0 to PHEV 20 compared with that going from the CV to the HEV 0 is for the EPRI case almost the same, while it is considerably less in the NREL case, or only around a half of the EPRI savings.

Table 8 shows the savings in energy cost for each set of specifications. For the difference PHEV 20 – CV, the EPRI specifications provide 20 % higher savings than the NREL specifications. For the difference PHEV – HEV 0, the EPRI specifications provide twice as large savings as NREL specifications. EPRI has a significantly higher efficiency for the plug-in options.

TOTAL COSTS

The total costs per km are shown in Figure 4. For the CV option the energy cost is a very significant part of the total cost. When hybridization and AER increases, the energy cost turns relatively less significant. In the EPRI case (EPRI specifications and EPRI average cost method), the PHEV 20 and the EV 350 have lowest and highest cost, respectively. The HEV, the PHEV 20, and the PHEV 40 have all lower specific cost than the conventional vehicle. The optimal vehicle (lowest costs) is thus in this case a PHEV with a relatively short range, the PHEV 20.

For the NREL case, the HEV 0 has the lowest cost followed by the CV. All the plug-in options have higher total cost than the fuel-only options. Each NREL option also has a higher total costs than the corresponding EPRI vehicle.

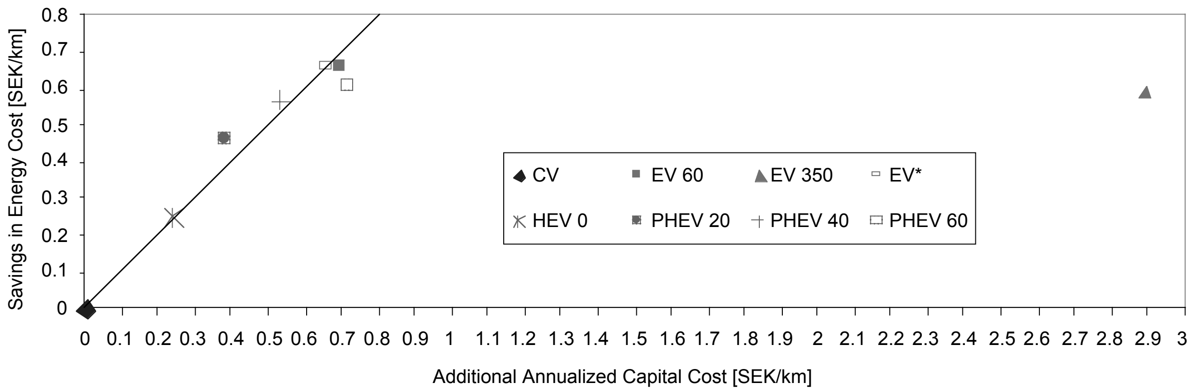

Figure 5. Savings in driving energy cost vs. additional capital cost for different vehicles relative to the CV (origo). EPRI specification and average cost method assumed.

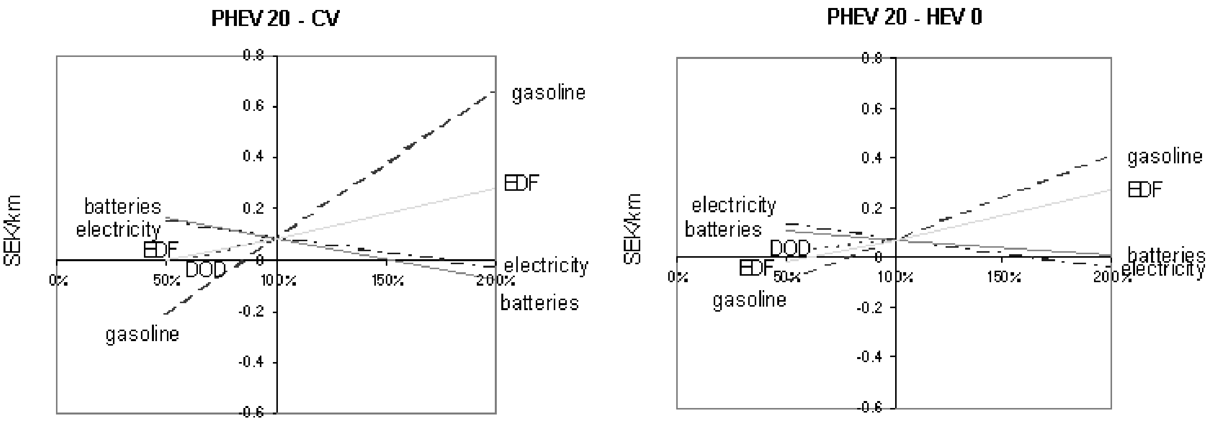

Figure 6. Sensitivity in savings of PHEV 20 relative to the CV and the HEV 0, respectively. (EPRI specifications and average cost method.)

There is a significant difference in the incremental economic performance between PHEV 20 and HEV 0 in the EPRI and NREL case, respectively. The extra vehicle capital cost per unit of savings in driving energy cost is about six times higher in the NREL case than in the EPRI one. A factor of three is due to the capital cost differences and a factor of two stems from the energy cost savings as seen in Tables 7 and 8, respectively. This difference explains the different results concerning the viability of extending the HEV into a plug-in vehicle.

The economic performance of the EPRI hybrid vehicle options compared to the conventional vehicle is further depicted in Fig 5. The line indicates the equality of additional capital costs vs. energy costs savings. The HEV 0, PHEV 20, PHEV 40, and EV * all offer positive net savings compared to CVs, with the largest savings for the PHEV 20.

The EV 350, the only EV option with the same range as the CV and hybrid options, has the worst economic performance of all the options. This is basically related to the very significant cost of electricity storage. A second reason, less significant though, is the lowering in efficiency due to the increase in the vehicle mass. Electricity storage would have to be considerably lower in price than assumed here to be able to have comparable long ranges with all-electric traction at compatible costs. The EV * is the only electric car option with an equal economic performance to the CV, however with a much shorter range (88 km or 55 US miles) than the CV and hybrid options. Thus, Swedish conditions make an all-electric vehicle with a short but still reasonable range a competitive option. In fact electric cars with ranges below 88 km would give savings in comparison to the CV. It should be noticed that the differences in driving costs between the EV 60 and EV * are very small, since they have similar energy efficiency. The EV 60 is basically a car which runs cheaper on electricity and has somewhat smaller capital cost than the PHEV 60 (no ICE traction but larger motor).

COST SENSITIVITY

What about the savings when deviating from the condition applied so far? We look specifically at the sensitivity of the saving achieved when going to a PHEV 20 from a CV and an HEV 0, respectively, Figs 6 and 7. Generally, considering changes in costs, a higher price of gasoline would increase the savings of a PHEV relative to both the CV and the HEV 0, while higher prices of electricity and batteries would decrease the savings.

Not only the overall economics for PHEV 20, but also the sensitivity to changes in parameters differs between the EPRI and NREL case. This is due to not only the specifications and cost methods used, but also to the operation modes. There is a distinction between the NREL and EPRI PHEVs regarding sen-

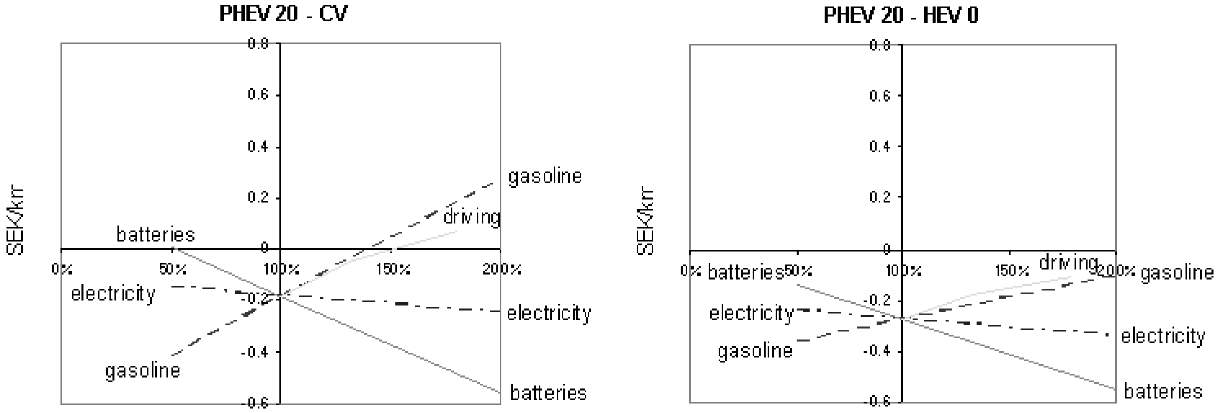

Figure 7. Sensitivity in savings of PHEV 20 relative to the CV and the HEV 0, respectively. (NREL specifications and cost method.)

sitivity to driving distance and driving patterns. In the NREL case, the driving patterns are not significant (blended operation) just the distance. However, in the EPRI case it is the other way around, the EDF is more important than the actual driving distance. It is important to notice that driving patterns and EDF are related to the driving distance, though. Changes in annual driving distance is accompanied by a probable lowering of EDF (compare Table 5). The blended operation of the NREL PHEVs makes their energy savings less for shorter driving distances but they increases more for longer distances. The use of the stored electricity is spread out over a larger distance due to the blending with engine traction thus increasing the sensitivity to driving distance. Compared to the EPRI vehicle, the less energy savings for shorter distances makes the NREL PHEV less sensitive to the electricity price. The larger incremental battery for and different battery make-ups makes it more vulnerable to battery costs, though.

In the EPRI case, Fig 6, PHEV 20 has in the base case, as we have seen, a better economic performance than both the HEV 0 and the CV. Prices of electricity would have to be more than 50 % higher than the 2004 price to make PHEV 20 not competitive with the CV and 100 % with the HEV 0. With gasoline price 15 % lower (or approx. 8.5 SEK/l) the PHEVs is not cost-efficient, though. In 2004, taxes on gasoline were 68 % of the total price, so high European-like petrol taxes is a prerequisites for the economic viability. For the EPRI PHEV, even at a considerably low EDF like 0.25 (50 % of original), the PHEV is still optimal compared to CV and at an EDF of around 0.3 compared to HEV 0. In the NREL case, PHEVs are not cost efficient. The HEV 0 outperforms the PHEV 20 under a wide range of conditions, even though the plug-in vehicle can compete with the CV for reasonable changes in pump prices and battery costs.

Discussion

Vehicle costs are crucial to the results of this study. Thus until real hybrid vehicle options are manufactured and their real capital cost and operation cost are seen, highly accurate calculations can not be made. Significantly higher prices of electric traction components than assumed here would lower the economic performance of hybrid options. However, both the resources for cost estimates used here share the main cost functions for components for future production of 100 000 units per year and specifically the cost of the energy storage. The results of this study also strongly depend on the handling and level of mark-ups. A higher level of mark-ups would increase the incremental difference of hybridized options compared to CV, resulting in a lower than estimated economic competitiveness. The calculated total costs excludes costs for maintenance. It appears that maintenance costs could decrease with increased hybridization, because maintenance costs of electric traction components are lower than for engine traction ones (EPRI 2001). It will depend on the operation mode and specification, though, with probably lower cost for all-electric range vehicles compared to vehicles using blended operation.

The results here are based on modeling of vehicles based on typical constructions and aerodynamics of current US midsize sedan. The use of light-weight materials and constructions and better aerodynamics could increase the efficiency of each vehicle option consider here. The use of advanced materials and constructions could increase the capital cost and lower the energy cost for each vehicle option. The incremental difference in capital cost of hybrid options with respect to CV can decrease also, because of lower battery capacity requirement (EPRI 2001). How the overall economic competiveness will change for different vehicle options needs more investigation, though.

The results showed that the performance specification and system design are crucial for the economic viability of going to a PHEV when starting from an HEV. Introducing cars building on new technical concepts as plug-in will possibly involve new performance profiles. The NREL PHEV was supposed to meet all the performances of conventional car, meaning it will perform better in some, while in the EPRI case trade-offs between performance and costs have been made to have all-electric operation at reasonable costs (Simpson 2006, EPRI 2001). This compromising in performance in the EPRI case contributes to its lower marginal vehicle costs for having a plug-in, although there are also other factors as the mark-ups. The EPRI all-electric range design also achieved about twice as much fuel savings as the NREL car using blended operation.

The EPRI and NREL car specifications and designs also reflect the different perspectives we can have on PHEV. The NREL PHEV car with its blended operation can be seen as a conventional fuel car with an efficiency enhancing electric hybrid where the plug-in possibility can make further contributions to fuel efficiency. The EPRI PHEV car is more easily percieved as an electric vehicle (and thus immanent efficient) with a range enhancing kit (possibly compromising the efficiency somewhat, though). The perspective is important for the manufacturers in their thinking about what development to achieve and how to market it. Williander (2006) has shown that for "green" innovation to succeed, it is required that the manufacturers invest in new technology and think of producing an attractive product promoting the environment instead of an environment-friendly variant of an already existing product. It can be noted that the newly by GM launched plug-in concept car, Chevrolet Volt, includes a new series hybrid drivetrain (all-electric operation) with a relatively small engine working as a generator only for maintaining charge for range extension. Top executives of GM also claim that they believe in the electrification of the car. The vehicle included advanced light weight materials in its construction, which would help increasing power to mass ratio of the vehicle. This is an indication that manufacturers are beginning to realize the advantages of all-electric operation and are trying to find technical approaches for making their performance more acceptable. GM claims that no trade-offs in performance would be needed (Green Car Congress 2007).

What type of product it is and what to compare performance with is important for customer preferences. The sustained top speed of the EPRI PHEV is considerably lower than that of the CV or HEV 0. But even this top speed is significantly higher than the highway speed limits in Sweden or any other country with speed limits. And in fact there are performance categories like acceleration from zero to mid range speeds in which EPRI PHEVs would overpass the CV. So far, high power rates for achieving comfortable acceleration and low aerodynamic drag for fuel savings have implied high top speeds which now seems strongly incorporated in the preferences.

The market for PHEV will depend on the benefits of the customers. Driving patterns vary among car drivers. For introduction of PHEVs it may be enough that some share of the car owners have the possibility to utilise grid electricity for most of their driving and thus save fuel and driving costs to a large extent. A larger diffusion is dependent on the development of the costs for larger groups of customers as well as more specific factors such as recharging capability and convenience.

The energy analysis here is limited to energy use in the vehicles. The PHEVs achieve fuel savings compared to the CV and the HEV. However the level of reduction of total CO_2 emissions is strongly dependent on the CO2 intensity of the electricity production. With electricity from coal condensing power, the NREL and EPRI vehicle specifications result in similar levels of emission of CO_2 for each vehicle denomination. With carbon neutral power, the EPRI PHEV options have considerably lower CO_2 emissions than the NREL PHEV options. The carbon intensity of the electricity system can thus be important not only for the overall CO2 effects of PHEVs, but also for effects of blended operation vs. all-electric modes. However, the long-term effects of PHEVs on CO_2 emissions is difficult to track down and will depend crucially on the development of the sourrounding energy and electricity system. For instance, Swedish electricity is low in CO_2 intensity compared to most other OECD countries. This could be a possible incentive for introduction of plug-in vehicles in Sweden. It has been argued though, that on the margin also Swedish electricity demand is dependent on foreign coal power due to due to the interconnections with the electricity systems of the neighbouring countries. But also, from a technical perspective it seems easier to mitigate CO_2 emissions from fossil stationary power plants than from mobile sources (like vehicles). New stationary fossil fuel powered plants could be upgraded with CO_2 sequestration technology. Therefore PHEVs might turn into a technically feasible way to use fossil fuels in transportation with no or low carbon emissions, especially when combined with biofuels for the engine.

Conclusions

We have investigated if plug-in hybrid electric vehicles (PHEVs) could become a viable option under the European conditions with relatively high fuel prices. We have here evaluated the viability of PHEVs by applying two different sets of midsize vehicle specifications and car costs methods suggested by EPRI and NREL, respectively, and then evaluated ownership economics under Swedish condition concering energy prices and driving patterns. Lifetime costs related to driving energy and vehicle capital have been considered. Vehicle capital costs are based on estimations for a level of production of components of 100 000 units per year with technical advances expected for year 2010. The EPRI vehicle specifications include trade-offs between cost and performance and are designed for all-electric operation. The NREL specifications have a somewhat higher performance and are designed for a blended operation.

The results indicate that the economic viability of PHEVs will depend on the specification of the vehicles and cost methods applied. PHEVs with a shorter all-electric range (EPRI specifications and cost methods) are a viable option compared to both conventional vehicles (CVs) and HEVs under Swedish conditions. Sustained fuel prices at this level are important for the conclusion. Driving patterns influence the optimal all-electric range. It was found that the optimal AER of the ones evaluated (32, 64 and 96 km) was 32 km. PHEVs have better economic performance than total electric vehicles with the same range. The vehicle specifications and blended operation assumed in the NREL case made the PHEV less compatible. Also the cost method applied in this case contributed to the result.

To make the energy efficient PHEVs a real option it is thus important to focus vehicle development on vehicles with all-electric range and to keep fuel prices for cars at least on current Western European level.

Acknowledgement

Financial support from The Swedish Energy Agency, Göteborg Energi, Göteborg Energi Research Foundation, and The European Energy Pathways project, established within the Alliance for Global Sustainability, is gratefully acknowledged.

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Glossary

AER	All-Electric Range: total distance that a PHEV can operate on electricity from the (totally charged) battery from the beginning of a driving profile till the engine turns on (Markel and Simpson 2006). In blended operation the engine and the battery-motor combination work together at the same time.
ANL	Argonne National Laboratory
CV	Conventional vehicle: vehicle with only reciprocating internal combustion engine traction
DOD	Depth of Discharge: allowed discharge fraction of the total energy capacity of a battery
DOH	Degree of Hybridization: fraction of the total power of the vehicle that accounts for the electric traction drive components (Simpson and Markel 2006)
EDF	Electric Driving Fraction: fraction of the annual driving distance driven on electricity
EV	Electric Vehicle: vehicle that is powered by electricity entirely
HEV	Hybrid Electric Vehicle: vehicles, whose drive train includes an engine and a battery-motor combination. In these vehicles some of the energy from braking is saved as electrical energy in the battery and then the battery-motor combination can provide power, this is typically called regenerative braking. This configuration avoids low efficiency engine operation like idling and low load.
MWP	Mileage Weighted Probability: fraction of the annual driving mileage driven on electricity
PHEV	Plug-in Hybrid Electric Vehicle: a HEV with capability to charge a larger battery from the grid.
SOC	State of Charge: remaining fraction of the total energy capacity in the battery (Markel and Simpson 2006)