Plug-in Hybrid Electric Vehicles: A Viable Option for Sweden?

Thesis for the Degree of Master of Science in Industrial Ecology

ANGEL D. RAMIREZ MOSQUERA

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Division of Physical Resource Theory
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ABSTRACT

Transportation accounts for around one third of CO2 emissions in Sweden. Personal cars in Sweden have one of the highest average fuel demands per km 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 the Swedish electricity production is highly carbon neutral; therefore it may be desirable to use electricity from the grid to power personal vehicles.

Here we investigate under which circumstances plug-in extensions of hybrids with different all-electric range are cost-effective options for energy and fuel savings. It is shown that plug-ins with a reasonably small all-electric range (30-40 km) for a wide range of circumstances could become a viable option in comparison to conventional, hybrid electric, and electric vehicles. The implications of large scale application of such a system in Sweden on the energy demand, electricity, and the potential for bioenergy to cover all the personal transport demands are outlined.

Keywords: Car transportation, plug-in hybrid electric vehicles, cost-efficiency, energy savings, CO2 emissions, Sweden

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1 Introduction

Today, climate change is by many perceived as the 21st century's greatest environmental challenge. The main driver of climate change is man-made carbon dioxide (CO2) emission. In Sweden transport accounted for about 36% the total emissions of CO2 in year 2003 (calculated from Swedish Energy Agency 2005a, p. 7). The personal vehicle system is dominated by internal combustion engine cars. New personal cars in Sweden have the highest emissions of CO2 in average in the European Union. (Vägverket 2004, p. 1 (183 of 220)). The number of cars and yearly driving distances are growing (Vägverket 2003, p. 3). Significant reduction of CO2 emissions from transportation requires increased efficiency and changes of the transportation energy source away from fossil fuels.

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, which demands mandatory improvements in CO2 emissions.

Drivetrain technology options today are conventional vehicles and electric vehicles, although the last group is very small. Current new options are hybrid vehicles, like the Toyota Prius, which provide a significant increase in efficiency.

Nowadays, a new option is being considered: plug-in hybrid vehicles. They are vehicles which can work as normal hybrids, and also as electric vehicles for a limited range using electricity from the grid (when designed for this purpose). In general, hybrid technologies have a higher capital cost than comparable conventional cars provided that hybrid vehicles include a motor-battery combination. The energy storage cost increases as the battery capacity (and the all-electric range) increases.

It is reasonable to assume that car users typically try to buy vehicles that provide the highest utility at the lowest price. Lowering the environmental load while increasing economic performance is difficult; however it seems that plug-in hybrids under certain conditions would give economic benefits to their owners, while helping to reduce its environmental load. High pump prices would help the viability of plug-in hybrid vehicles compared to conventional and hybrid vehicles. In this study we investigate to what extent plug-in hybrid technology can be a viable option for Sweden.

The objectives of the study are:

- determine if under Swedish conditions, plug-in hybrid vehicles would be an economically viable option for car owners in comparison to conventional vehicles and identify the most important conditions for this viability.
- identify the most convenient all-electric range under various conditions.
- determine if electric vehicles would be more adequate than plug-in hybrid vehicles.
- determine how the energy used by the personal vehicle system in Sweden and the associated CO2 emissions would change, if plug-in hybrid vehicles are utilized on a large scale.

- illuminate the long-term use of biomass in transportation with plug-in hybrid vehicles using biofuels and electricity produced from bioenergy.

Chapter 2 gives a review of hybrid vehicle development and an introduction to some concepts used in the study. Chapter 3 explains the used methodology. Chapter 4 presents the results obtained. In Chapter 5, a discussion about some critical issues for plug-in vehicles is performed. Finally Chapter 6 provides some conclusions.

2 Plug-in hybrid vehicle technology

In this chapter, some concepts that are used in this study and facilitate the understanding of hybrid vehicle technology are introduced. A brief summary of the important facts in hybrid vehicle history and a review of involved companies' development directions and demonstration projects in recent years are presented. Finally a review of plug-in hybrid vehicles development is performed.

2.1 Hybrid technologies

Hybrid electric vehicles (HEV) are vehicles, whose drivetrain includes an engine and a battery-motor combination. This is the case of the commercially available hybrids like the Toyota Prius, Honda Insight, Ford Escape, etc. In comparison to conventional vehicles, these vehicles avoid low-efficiency engine operation modes like idling and low load. An additional advantage is that 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*.

There are two main types of drivetrain configurations, series and parallel HEV. A combined system is also possible.

In *series HEVs*, the electric motor provides all the propulsion. The electricity can come from the battery pack or from the engine-generator. The engine is always operated in the most efficient regime. The engine-generator and the regenerative braking can recharge the battery pack. A control unit determines when and how the power is utilized and distributed. (Hybrid Center n.d.).

In *parallel HEVs*, both the ICE and the electric motor provide power to the wheels. This configuration can use a smaller battery pack, and uses regenerative power for battery recharging. Under low power requirements, the motor could provide power to charge the battery. Since the engine is directly connected to the wheels, parallel hybrids are quite efficient in highway driving. Honda has used this concept for its HEVs. In series drivetrains the internal combustion engine (ICE) is typically smaller and the battery-motor is more powerful than in parallel hybrids. The larger battery-motor and the need for a generator add capital cost to series HEVs and typically they are more expensive than parallel HEVs. Series hybrids perform better in non-continuous driving conditions, because the ICE always works efficiently (Hybrid Center n.d.).

Parallel/Series HEVs, are a combination of both systems. The ICE can either drive the wheels directly (as in a parallel configuration) or be disconnected and the motor can provide all the power (as in a series configuration). Toyota has used this concept in its HEV system. The result is a more efficient operation of the engine more often, either in stop and go driving (city) or in highway driving. Thus it performs better than the other two systems. On the other hand it is more expensive because it requires a larger battery-motor combination and a complex computer power control (Hybrid Center n.d.).

Mild hybrids is a term used to describe vehicles that use the ICE as the main source of propulsion and the electric motor provides extra power when it is required. The motor can not operate alone and the electric motor/generator can either recharge the battery or consume the stored electricity, but never both at the same time (About n.d.).

In *full hybrid vehicles*, the battery-motor and the ICE are arranged such that, under some conditions the electric motor could provide all the propulsion. Full hybrids can generate and consume electricity at the same time (About n.d.).

A *Plug-in hybrid vehicle* (PHEV) is a HEV with plug-in capabilities, meaning that the battery can be charged with electricity from the electricity grid. The battery-motor can even provide power to run on electricity only for a certain range determined by the capacity of the installed battery.

When discussing PHEVs two terms are common, the *all-electric range* (AER) and the *degree of hybridization* (DOH). The AER is the total distance that a PHEV can operate from the beginning of a driving profile till the engine turns on. In this case the energy comes only from the stored electricity in the batteries. DOH is the fraction of the total power of the vehicle that accounts for the electric traction drive components (Markel and Simpson 2006, p. 2).

In the design, a PHEV can be optimized for *blended operation* or AER. In a blended operation the engine and the battery-motor combination work together at the same time. The exact way in which they work together depends on the control strategy. In AER operation, the vehicle uses the battery-motor combination when the battery is charged. The vehicle then uses the engine and fuel from the tank mainly as a range extender. High performance situations (high power requirements) would possibly be driven in blended operation. The focus of design criteria on either blended operation or AER will depend on performance and costs. However prices of energy and associated environmental aspects should also be taken into consideration.

An *electric vehicle* (EV) is a vehicle that is powered by electricity entirely (Wordnet n.d.).

2.2 HEV market development

Commercially available HEVs, began with the Toyota Prius in 1997 for the Japanese market. In 1997, the Audi A4 Avant Duo was introduced as the first European hybrid; the car was not a commercial success and production was suspended. However European car manufacturers focused their development on diesel engines (Hybridcars.com n.d.).

Between 1997 and 1999, some electric vehicles (EVs) where introduced in California, they were not a commercial success. The all-electric programs were dropped (Hybridcars.com n.d.).

In 1999, Honda launched the two-door Insight, which is the first HEV introduced in the US market (Hybridcars.com n.d.). Honda HEV is based on electric power assist mode, which means that the electric motor provides additional power when it is needed, but the engine is still the main source of propulsion (About n.d.).

In 2000, Toyota introduced the 4-door Toyota Prius in the US market (Hybridcars.com n.d.). The Toyota Hybrid Technology is based in a configuration that would allow operation of the electric motor alone under certain conditions (About n.d.).

In 2004, The Toyota Prius II won the 2004 Car of the Year Awards from Motor Trend Magazine and the North American Auto Show. The demand for the car was better than Toyota expected and the production had to be increased from 36 000 to 47 000 units yearly for the US market. (Hybridcars.com n.d.).

Today, there are several HEVs on the market like: Toyota Prius, Ford Escape Hybrid, Mercury Mariner Hybrid, Toyota Highlander, and Lexus RX 400h.

2.3 Plug-in hybrid vehicle development

2.3.1 Companies and new partnerships

The development of PHEV technology so far has been carried out by companies and consortiums and developers of new solutions, based on HEV with no plug-in capabilities. Car manufacturers like Toyota, Honda, Nissan, Ford, GM and DaimlerChrysler have PHEV projects and concepts; however demonstration cars often come from companies which have developed systems and upgrade kits for conversion of hybrid vehicles. Here is presented a short review of some known and publicly expressed directions and plans of car manufacturers.

In 2006, Toyota Motor North America expressed that Toyota is working on PHEVs as well as considering flex fuel vehicles for the US market. The president of Toyota has said that Toyota would double the number of hybrid vehicles models, including PHEVs. He also told that PHEVs have significant effect on reducing CO2 and on abatement of air pollution. Toyota works on a next generation Prius with an all-electric range of about 14.5 km (Green Car Congress 2006).

In 2005, Toyota exposed a concept house which included a plug-in Prius. The Prius was able to provide energy to the house during emergencies. This kind of technology is expected for 2010 according to Toyota. It should be noticed that Toyota, in a response to a group in favor of PHEVs in 2005, had stated that the electric vehicle is not non-polluting if the electricity to recharge the batteries is not green, and that batteries still require development (Green Car Congress 2005).

In 2006, Nissan ended its previous agreement with Toyota, which was providing its hybrid system for Nissan models. Nissan will develop its own PHEV compact car, which would use lithium-ion battery packs (Yomiuri Shimbun cited in Green Car Congress 2006). Before that, in 2005, Nissan had told that hybrid vehicles were not a good business and were a solution just for niche markets (Green Car Congress 2005).

DaimlerChrysler is working with the Environmental Power Research Institute (EPRI) on the development and field testing of plug-in Sprinter vans. The project includes the test of six different PHEV systems in different cities of the world. The project is in the fleet feasibility testing phase. The program has as objectives to collect performance and field data, to verify durability of batteries, and to use results for further improving of prototypes. The project would use six Sprinter vans with different combinations of engines (diesel or gasoline) and batteries (NiMH or lithium-ion). All use the same 90 kW motor. There are two Cargo vans in Germany, one uses a diesel engine, and other one uses gasoline, both use NiMH batteries. In the US, three of the four vans use Li-ion batteries, the other one uses NiMH, two of them have gasoline engines and the other two have diesel engines. DaimlerChrysler is using its model Sprinter van as a platform for the test of plug-in hybrid and fuel cells technology (EPRI cited in Green Car Congress 2006).

Besides, DaimlerChrysler, Bayerischen Motoren Werken (BMW) and General Motors (GM) are working together in the development of a “two-mode” hybrid system for cars (US Department of Energy 2005). The new Saab Biopower Hybrid, incorporates this hybrid transmission. The vehicle has flex-fuel capabilities and a 300 volts lithium-ion battery pack, a 38 kW motor, an integrated starter/generator and all-wheel drive with the electric power for the rear wheels. It is believed that the vehicle would include plug-in capabilities. The two-mode transmission can be used for electric-only operation, supplying extra torque or regenerative braking (Green Car Congress 2006).

In 2006, The GM Vice Chairman said that the GM is not putting all the eggs in the hydrogen basket and that GM is studying PHEVs, but still they are considering the battery issues. In 2007, GM has introduced their new concept plug-in hybrid vehicle, the Chevrolet Volt, in the North American International Auto show. The Volt would have a series drivetrain and an AER of 40 miles (64 km). The motor peak power is 120 kW, while the engine-generator power is 53 kW. The basic control strategy is to run the vehicle in all-electric operation and allow a DOD of 70%. The car will be manufactured with light materials. GM claims that there will be no trade-offs for customers, with accelerations from 0 to 96 km/h between 8 and 8.5 seconds and top speed would be 160 km/h, although it is claimed that it would be able to reach 196 km/h for limited periods. The vehicle would use Li-ion batteries. Production of the car would depend on battery development (Green Car Congress 2007).

Ford is investigating PHEV technology; however they still claim that there are three issues of significance, which are battery life, warranty coverage and safety. In 2006, the Ford Sustainable Development Strategy Group when asked about the Hymotion upgrade PHEV kit for the Ford Escape, they answered that they encourage the creativity of their customers (Lifestyles of Health and Sustainability conference in Santa Monica cited in Green Car Congress 2006).

Hymotion is a Canadian company founded in 2005, which in 2006 unveiled PHEV upgrade kits for the hybrid vehicles Toyota Prius and Ford Escape. Hymotion technical approach is to supplement the original hybrid vehicles batteries with additional lithium-ion battery packs for the plug-in energy storage. The batteries are manufactured in Asia. The first offer includes the 5kWh L5 for the Prius and the 12kWh L12 for the Ford Escape SUV. Hymotion is developing upgrade kit systems for other hybrid vehicles in the market like the Lexus RX400h, Toyota Camry Hybrid and Toyota Highlander Hybrid. The original plans are to sell the kits for fleets owners. Orders of more than 100 L5 kits will be at US$ 9500, and orders greater than 1000 will be at US$ 6500. There is no price available for the 12 kWh systems. The estimated all-electric range is 50 km and the combined estimated fuel economy is 100 US miles per gallon for the L5, while 80 km and 60 mpg for the L12. (Green Car Congress 2006).

EDrive Systems and Clean Tech are two US companies affiliated with EnergyCS. EDrive systems have converted some Prius to PHEV, and it is working in the development of conversions for other hybrid vehicles. This system would provide an estimated AER of 56 km and an estimated combined fuel economy of 100 to 150 mpg. The price of the EDrive kit would be between US$ 10000 and 12000. These companies are working with Amberjac Projects in UK, for the conversion of cars in Europe (Green Car Congress 2006). EDrive uses lithium-ion batteries that replace the original battery pack (Green Car Congress 2005).

Two US companies, Hybrids-Plus and A123Systems, an advanced batteries developer, are also developing PHEV conversions (Green Car Congress 2006).

AFS Trinity Power Corporation is a US company focused on the development of advanced energy storage technologies for hybrid and plug-in hybrid vehicles, power quality, and aerospace applications. They are working together with Ricardo, an automotive engineering firm, in the development of the AFS Trinity Extreme Hybrid (XH) which would have an AER of 40 US miles with the same performance as when operated as a hybrid vehicle. In the hybrid mode it can be operated up to more than 450 US miles (Green Car Congress 2006).

Think NORDIC AS (Norway) together with Raufoss Fuel Systems is developing a fuel cell plug-in hybrid vehicle. The vehicle Th!nk Hydrogen would offer a 300 km driving range, half derived from the electric grid and half from the hydrogen fuel cell. The plan was to have demonstration prototypes by 2006 (Green Car Congress 2005).

PML Flightlink and Synergy Innovations presented a series hybrid converted MINI at the British Motor Show, called the MINI QED. It is a demonstration and test-vehicle. The vehicle uses four motors in its wheels, a 21 kWh lithium-polymer battery pack and a 250 cubic centimeters ICE. The vehicle uses a 230V, 11 Farad ultracapacitor to provide high power for acceleration and for regenerative braking (Green Car Congress 2006).

SVE, an electric vehicle developer created by two French companies, launched the Cleanova Plus which combines a Li-ion battery and a permanent magnet AC synchronous motor-generator with a spark ignition ICE, which operates entirely with ethanol as a range extender. The Cleanova Plus has been tested with the French post office (La Poste) (Green Car Congress 2006).

There are also groups and network of companies and municipalities and others that work in the push of PHEVs. The Plug-in Partners campaign launched by the City of Austin and Austin Energy has been joined by 60 cities in the US, like Los Angeles, Dallas, Boston, Philadelphia, Chicago, San Francisco, Baltimore and Phoenix, as well as by environmental and national security organizations and business and utility partners. Some partners companies are: AutoNation, Inc, the US largest automotive retailer, Pacific Gas and Electric and AFS Trinity. The coalition is working for creating markets by pushing fleet orders. They have the "Plug-In Hybrid 50-City Plan" for building up market for PHEV around US. They are also working in a petition for the consumers to express interest in PHEVs (Plug-In Partners cited in Green Car Congress 2006).

The Plug-in Hybrid Development Consortium was founded in August 2005 by Raser Technologies, Pacific Gas and Electric, Maxwell Technologies, and Electrovaya to join component suppliers in order to accelerate the production of PHEVs. The Consortium has as a goal to develop 20 to 50 US AER systems, and to use the ICE for longer distances. Members of the Plug-in Hybrid Development Consortium are: A123 Systems (Lithium-ion batteries), AES Corporation (Power company), Brusa (Power electronics), Daiken (Lithium-ion batteries), Delta-Q Technologies (Power electronics), Electrovaya (Lithium-ion batteries), ENAX (Lithium-ion batteries), International Battery (Lithium-ion batteries), Maxwell Technologies (Ultracapacitors and energy storage), NexxtDrive Ltd (Transmissions), PG&E (Utility), Raser Technologies (Electric motors), Solomon Technologies (Electric drive systems), Southern California Edison (Utility) and Hydrogenics (Hydrogen generation and fuel cells) (Green Car Congress 2006).

CalCars, the California Cars Initiative for Plug-in hybrids, is a group of entrepreneurs, environmentalists, engineers and other citizens working in the adoption of non-polluting vehicles. They support all types of alternative technologies, like hybrid, electric, biofuel and natural gas vehicles. In the last years their focus has been in PHEVs. CalCars made in 2004 the first Prius conversion, based on lead acid battery packs to prove that the technology works (The California Cars Initiative n.d).

2.3.2 Battery technology

One very important component of PHEVs is the battery pack. Different electrochemical cells have been used in prototypes and concepts. Lead acid batteries and nickel-cadmium batteries are not attractive, because of low specific energy and inadequate cycle life. There are mainly two advanced technologies that can be taken into account as part of the PHEV at present and in the future: nickel metal hydride (NiMH) and lithium-ion (Li-ion) (EPRI 2004, p. 2-4).

In Table 2-1 examples of specific energy and power for NiMH and Li-ion batteries in different levels of development are presented. Cases for reasonable high power and high energy are presented.

Table 2-1 Comparison of energy and power of some NiMH and Li-ion batteries.

	NiMH[a]		Li-ion[b]	
	Texaco Ovonic Battery Systems	Panasonic EV Energy	GS/JSB (Japan)	GS/JSB (Japan)
Specific Energy [Wh/kg]	71	~40	100	25
Specific Power [W/kg]	~390	>1000	700	2000
Power/Energy [W/Wh]	5.4	25	7	80

[a] (EPRI 2004, p. 2-6)
[b] (EPRI 2004, p. 2-7)

Nickel metal hydride batteries are the technology being used in current HEVs like Toyota's models. NiMH battery technology itself is mature, although the manufacturing is not mature enough yet (Pesaran 2006). One of NiMH advantages is its long battery life cycle. In fact apparently the life of one NiMH battery pack would be enough for the whole life span of a PHEV (EPRI 2004, p. 1-2).

A less mature technology is Li-ion, which offers better energy and power capabilities (see Table 2-1). However the technology itself and the manufacturing technology are not in a mature phase. Their cycle life capabilities are typically lower than NiMH (Figure of Rosenkranz cited in Markel and Simpson 2006, p. 4).

Battery life depends strongly on the use of the batteries characterized by parameters like *state-of-charge* (SOC) and *depth-of-discharge* (DOD). SOC is the at any instant remaining fraction of the total energy capacity in the battery (Markel and Simpson 2006, p. 2). DOD is the fraction of the total energy capacity that in a specific design is intended to be supplied by the battery. Once the energy capacity for providing propulsion of a battery is determined, the allowed DOD (or SOC) is the most important parameter in defining the actual size of PHEV battery.

NREL indicates that NiMH batteries can achieve 4000 cycles, when the 70% DOD is used, while for Li-ion batteries to achieve the same cycle life, the DOD should be 50% (Markel and Simpson 2006, p. 4).

It should be noticed that Li-ion batteries are used by conversion kits developers like Hymotion and EDrive (section 2.3.1).

Regarding power requirements and rapid energy storage, an important contribution to electric traction technology could be ultracapacitors, which can be used for supplement high power discharge and recharge. These characteristics would be very attractive for high acceleration and regenerative braking. Ultracapacitors are being proposed in concepts like the MINI QED (Section 2.3.1).

2.3.3 Barriers to plug-in hybrid vehicles

There are some barriers to the upcoming of PHEVs. Many of the issues and disadvantages of PHEV technology have actually been expressed by car manufacturers.

For instance in 2006, John German of American Honda expressed concerns about the following points (Green Car Congress 2006):

- Battery weight and size, and performance demands. The batteries add weight, this would decrease performance. Additionally, it is not easy to find where to put batteries in the vehicle.
- Emissions control would be one order of magnitude higher, because the engine is off most of the time, and the catalytic converters need 250° C to function properly. Current emission control and fuel economy testing would have to be revised.
- The battery would require replacement at least once during vehicle life, because of deep discharge cycles and higher electrical loads.
- Cost effectiveness, it is not a good business for manufacturers or customers if gasoline is not more than US$ 3 per US gallon, or PHEV are subsidized, or there is a breakthrough in energy storage.
- Environmental considerations should include CO2 emission during electricity production and end-of-life battery disposal.

Toyota, in 2005, stated that the electric vehicle is not non-polluting if the electricity to recharge the batteries is polluting, and that batteries still require development (Green Car Congress 2005).

In 2006, Niel Golightly, the Ford Motor Company's director of sustainable business strategies said that Ford is investigating PHEV, and they have found three barriers to production, which are battery life, warranty coverage, and safety (Green Car Congress 2006).

The production of GM's new concept plug-in hybrid vehicle, the Chevrolet Volt, introduced in the North American International Auto show 2007 would depend on battery development. The vehicle would use Li-ion batteries (Green Car Congress 2007).

3 Methodology

In this chapter, the methodology is explained. To determine whether PHEVs are a viable option for Sweden, we investigate the private benefits for owners based on savings in comparison to having a conventional vehicle including vehicle capital cost and energy cost. On the other hand social benefits as energy savings and climate benefits are also assessed. The vehicle options included are a conventional vehicle (CV), a hybrid electric vehicle (HEV 0) and three PHEVs with three different all electric ranges (32, 64 and 96 km, however marked by their range in US miles though, i.e., PHEV 20, PHEV 40 and PHEV 60). A review of the vehicle specifications is performed. An explanation is given of how the cost per km for capital and energy are calculated. The data used is presented through the whole chapter.

We have departed from an EPRI Technical Report (EPRI 2001) for defining specifications, efficiency, cost functions and price calculation method for the cars. A review of the EPRI Technical Report is presented in Appendix A. EPRI specifications are based on electric-only operation for a limited range. With the component sizes and cost functions, the costs of individual components are calculated. Than mark-up factors accounting for manufacturing, manufacturing overhead, warranty costs, manufacturing profits and dealer overhead and profits are used to obtain the retail price. The retail price is than annualized using simple discount for 10 years. The cost per year is divided by the annual driving distance for estimating the capital cost per km.

For comparison a different set of specifications and cost data have been applied: specifications and retail price calculation method presented by the US based National Renewable Energy Laboratory (NREL) (Simpson 2006). NREL specifications are based on a higher performance with blended operation.

For calculating the energy cost of PHEVs for the EPRI specifications, first the electric driving distance per year is estimated. This is done by using the average cumulative distribution of driving distance per day in Sweden. It is assumed that charging is done during nights and that daily driving distances equal to or lower than the AER are driven totally on electricity. The fuel driving distance is the total annual driving distance minus the electric driving distance. The total cost of electricity and fuel for the year is then calculated by using the electric-only efficiencies and fuel-only efficiencies defined by EPRI. Difference in efficiencies for highway driving and urban driving is taken into account. For calculating the driving 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 energy cost of conventional vehicles (CV) and HEVs are calculated using fuel consumption for the total driving distance.

The EPRI Technical Report (EPRI 2001) includes PHEVs with two different AERs, 32 km and 96 km. An additional plug-in option of 64 km has been added here. For comparing to EVs, three electric vehicle options of different ranges are defined, one with the same range as the longest PHEV AER, one with equal total range as the CV and hybrid options, and one with a range that would provide parity in cost per km with the CV.

To find the optimal options for different conditions, a spreadsheet program has been developed. In this program various conditions can be easily varied to evaluate how these will influence the relative savings of the vehicle options compared to the CV. Conditions that can be varied include the set of specifications, electric driving fraction (EDF[1]), gasoline prices and taxes, electricity prices and taxes, level of battery prices, discount rate and DOD. The main results are calculated as savings of each vehicle option compared to the CV in a total cost per km basis (capital and energy).

The effect on energy use is investigated by comparison to a forecasted energy use by CVs taking into account the growth in vehicle fleet and driving distance. The potential energy savings and CO2 emissions reduction are then assessed by estimating figures for all the vehicle options for different assumptions on the electricity supplied specifically to the cars. For estimating the bioenergy needed for powering a plug-in system relying totally on bioenergy, efficiency factors for obtaining biofuels and biopower from biomass are used. The total bioenergy demand is compared with the supply potential of Swedish biomass.

3.1 Vehicle performance and specifications

Component sizing is significant when it comes to capital cost and energy efficiency. In this work we are using the optimizations already made in modeling of PHEVs by the research institutes EPRI and NREL. EPRI specifications are used as base case. In Table 3-1 CV the performances of both the EPRI and NREL cars and the average new sold car in Sweden are shown. The NREL base CV has the lowest time for acceleration.

Table 3-1 Conventional vehicle performance (selected data).

	EPRI[a]	NREL[b]	2002 Sold in Sweden[c]
fuel consumption[d] [l/100km]	8.2	10.3	8.26
acceleration[s] 0-96 km/h[e]	9.3	8	10.2
top speed [km/h]	192	177	200

[a] (EPRI 2001, p. 2-5 , p. 2-2)
[b] (Simpson 2006, p. 5)
[c] (Sprei and Karlsson 2006, p. 6)
[d] NREL and EPRI is based on the US EPA test cycle, Sweden 2002 is based on the EU EDC cycle
[e] In the case of Sweden the acceleration is 0 to 100 km/h

Table 3-2 gives the predicted performance for the EPRI vehicle options. The PHEV options have higher acceleration than its comparable CV in the 0-48 km/h, the 0 to 96 km/h and the 64 to 96 km/h ranges, but lower acceleration capacity from 80 to 112 km/h. The sustained top speed of PHEVs is considerably lower than the CV or HEV. It must be considered that during high performance demands the PHEVs might work in blended operation. However it is expected that the driver should have the option to set the car to an EV-only mode (at least while there is charge in the battery). The

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[1] Electric Driving Fraction (EDF): the fraction of the annual driving distance which is drived on gasoline

performance of all NREL vehicles is supposed to reach the ones of the NREL base CV shown in Table 3-1.

Table 3-2 Predicted vehicle performance (EPRI 2001).

Performance category	Target	CV	HEV 0	PHEV 20	PHEV 60
acceleration[s] 0 to 48 km/h	-	3.5	3.1	3.0	3.0
acceleration[s] 0 to 96 km/h	9.5	9.3	8.7	8.9	8.9
acceleration[s] 64 to 96 km/h	-	4.6	4.2	4.3	4.3
acceleration[s] 80 to 112 km/h	5.1	4.5	5.2	5.2	5.2
sustained top speed [km/h]		192	192	157	155

In the Tables 3-3, 3-4 and 3-5 vehicle specifications for the two cases are shown. It should be taken into account that same denomination vehicles of EPRI and NREL are not totally comparable. NREL has higher performance targets than EPRI (Tables 3-1 and 3-2) and reaches them with blended operation, including a lower limit for engine size of 80 kW (Simpson 2006, p. 6). The EPRI approach is different, in using all-electric operation and performing some trade-offs between performance and cost while having a reasonably similar performance to the base CV (EPRI 2001, p. 2-1).

In the EPRI case when the battery size increases, the total power decreases and the DOH increases. In the NREL specifications when the battery size increases, the total power increases and the DOH increases, however limited to 35%. NREL has significantly bigger batteries for the same plug-in denomination because of the specified SOC window. NREL has a goal of 15 years of battery lifetime (Simpson 2006, p. 6). As the lifetime goal increases, SOC decreases.

Considering the power to mass ratio of the vehicles, it can be observed that in EPRI specifications (Table 3-3) the power to mass ratio decreases significantly as DOH increases, while in the NREL specifications (Table 3-4) power to mass ratio is practically kept constant at a considerably higher level than each 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 acceleration capacity.

The mass of components according to EPRI specifications can be found in Appendix D.

Table 3-3 EPRI vehicle specifications (EPRI 2001).

Vehicle	CV	HEV 0	PHEV 20	PHEV 40[b]	PHEV 60
curb mass [kg]	1499.5	1500.4	1558.55	1758	1708.9
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	64.01	65.9
DOH	0%	40%	46%	56%	66%
battery energy [kWh]		3.63	7.35	14.8	22.42
P/E ratio [1/h]		13.47	7.35	5.16	4.41
DOD[a]		80%	80%	80%	80%
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] Originally the DOD in EPRI was 100%, for battery life considerations it has been changed to 80%
The efficiencies are corrected with a factor of 0.9 to simulate real driving conditions.
[b] The battery energy and energy efficiencies of the PHEV 40 has been determined by an interpolation between PHEV 20 and PHEV 60 specifications

Table 3-4 NREL vehicle specifications (Simpson 2006).

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	124	130
power to mass ratio [W/kg]	85.4	80.0	81.0	81	79.5
DOH	0%	32%	35%	35%	35%
battery energy [kWh]		1.5	11.8	19	23.6
P/E ratio [1/h]		32.80	4.90	3.2	2.60
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

In accordance with the objectives of the study electric vehicles specifications were needed. The electric vehicles are defined in a different way. It is assumed that a power to mass ratio of 60 W/kg is enough for a totally electric vehicle. In this way the electric motor power (total power) is defined. Battery capacity is based on the same relation for AER to battery energy as for the PHEV 60 (i.e., 0.6 km/kWh). The ratio of motor to battery power is set to 0.7 for all the EVs. The EV energy efficiency (Wh/km) is estimated using a function which relates the electric-only efficiencies of the plug-in options to their masses. This assumes the same battery technology is used in the EVs as in the PHEVs (NiMH). The use of Li-ion battery and mass would imply lower total mass and therefore higher efficiency. Table 3-5 presents the EVs' specifications.

Table 3-5 Electric vehicles investigated in this study.

Vehicle	EV 60[a]	EV 350[a]	EV *[b]
curb mass [kg]	1729	3130	1708
engine power [kW]			
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	100%	100%	100%
battery energy [kWh]	22.4	130.8	20.1
P/E ratio [1/h]	6.61	2.05	7.12
DOD	80%	80%	80%
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
Fuel only efficiency city [l/100km]			
Fuel only efficiency Hwy [l/100km]			

[a] The EV 60 and EV 350 has a range of 96 km and 560 km respectively.

[b] The battery capacity for the EV* is calculated as the battery size for an EV that has the same total cost/km as the CV, which then gives the range.

3.2 Capital costs

3.2.1 Cost functions

Both EPRI and NREL apply the same cost functions for the vehicle components, Table 3-6. The cost functions are based on technological advances expected for the year 2010 and production levels of 100 000 units per year (EPRI 2001, p 2-10)

Table 3-6 Vehicle component cost functions (EPRI 2001).

Component	Function (Results in USD)
V-6 Engine	$10.9 \times kW_{engine} + 693$
L-4 Engine	$12 \times kW_{engine} + 424$
Engine Thermal	$0.236 \times kW_{engine}$
Motor	$13.70 \times kW_{motor} + 190$
Power Electronics	$7.075 \times kW_{motor} + 165$
Power Electronics Thermal	$1 \times kW_{motor} + 70$
Battery	$kWh_{battery} (11.1 \times P/E + 211.1)$
Pack Hardware	$5 \times kWh_{battery} + 460$
Pack Tray	$5 \times kWh_{battery} + 130$
Pack Thermal	$3 \times kWh_{battery} + 90$

3.2.2 Vehicle retail price

Three different methods have been used for estimating the vehicle retail prices from the cost of their components. The first method is called the (EPRI) Base Method (cited in EPRI 2001, p. 4-2). It is based on the costs of manufacturing, manufacturing overhead, warranty costs, manufacturing profits and dealer overhead and profits. Battery mark-ups are treated in a different way, though, and as a fixed value per battery (EPRI 2001, p. 4-2). The following formula describes the method for calculating the retail price *P*:

$$P_{Base} = \left(C_{components} \times m_{manufacturer} + C_{battery} + m_{battery}\right) \times m_{dealer} + C_{development} \quad (1)$$

Here C_y is the cost of component or process y and m_z is the mark-up factor of component or actor z.

The second method is called the (EPRI) ANL Method (cited in EPRI 2001, p. 4-2), and it is supposed to describe a situation where the electric components are supplied by outside suppliers. Manufacturing and dealer mark-ups are combined in a single one. Battery mark-ups are treated in the same way as in the Base Method (cited in EPRI 2001, p. 4-2). The method gives the retail price according to:

$$P_{ANL} = C_{electriccomponents} \times m_{electric} + C_{manufacturer} \times m_{combined} + C_{battery} + m_{battery} \quad (2)$$

These first two methods were used by EPRI (EPRI 2001). In this document, a result indicated just as EPRI method would mean that the result is obtained as an average of both EPRI Base and ANL methods.

The third way of calculating the price is using the costs without considering separately the batteries and considering a mark-up for manufacturer and dealer:

$$P_{NREL} = C_{components} \times m_{manufacturer} \times m_{dealer} \quad (3)$$

This way of calculating provides concordance with NREL prices. We will refer to it as the NREL method. In Table 3-6 the mark-ups for the different cost methods are presented.

Table 3-7 Mark-ups for three different cost methods.

Mark-up for	EPRI Base[a]	EPRI ANL[b]	NREL[c]
manufacturer	1.5	-	1.5
dealer	1.16	-	1.16
combined	-	2	-
electric	-	1.5	-

[a,b] EPRI 2001, p. 4-11

[c] Simpson 2006, p. 8 (based on EPRI Base)

The battery module mark-ups based on EPRI (2001, p. 4-11) are shown in Table 3-7.

Table 3-8 EPRI battery mark-ups in USD.

HEV 0	PHEV 20	PHEV 60
800	850	900

Considering the two EPRI methods only, the Base method will result in higher prices than the ANL method. When considering the NREL method also, this one results in the highest price, for the same specifications. It is important to notice that in the NREL method battery mark-ups are treated like every other component. This is very significant because while, with the EPRI methods, the part of the calculated vehicle retail price that accounts for the battery does vary significantly less with the battery size, with the NREL method it varies proportionally with the size. This implies a higher final retail price for the same battery capacity with the NREL method compared to the EPRI cases (at reasonably big battery sizes).

It should also be noted that the NREL PHEV specifications with the same denomination as EPRI have higher battery capacities (see Tables 3-3 and 3-4). Thus, the use of the NREL cost method and NREL specifications result in significantly higher vehicle prices than EPRI specifications with EPRI methods for the same PHEV denomination. The battery is the most important part of the incremental difference in retail price of PHEVs. The situation for the HEVs is different, since the NREL method at low battery capacities results in a low battery final price and the NREL specifications imply a lower battery capacity.

3.2.3 Non-variable costs

The non-variable costs are the ones that do not vary with drivetrain option (or at least not continuously). The most important non-variable cost is the glider, which do not vary in cost in the vehicle options studied here. 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, p. C-4). The NREL price for the midsize sedan glider is 17 390 USD including mark-ups (Simpson 2006, p. 5).

The transmission is also an important cost. For the EPRI vehicles the cost of this component is 1045 USD for the CV and 625 USD for the hybrid options (EPRI 2001, p. C-2). The cost of the CVs transmission is based on a normal automatic transmission, while the transmissions of the hybrid options are continuously variable transmissions. The last one would be less expensive because it has fewer components than the first one (EPRI 2001, p. 4-4).

There are other minor fixed costs that can be seen in Appendix B.

3.2.4 Annualized capital cost

The calculated retail price is annualized using the following formula:

$$C_{capital,km} = \left(\frac{1}{D}\right)\frac{r \times P}{1-e^{-rT}} \tag{4}$$

where $C_{capital,km}$ is the capital cost per km, D is the annual driving distance in km, r is the discount rate, P is the initial investment which is the calculated vehicle retail price P (in equations 1, 2 and 3) and T is the number of years to pay. The base values used for r and T are 0.05and 10 years, respectively. D is presented in Table 3-12.

3.3 Energy cost

3.3.1 All-electric operation

The electric driving energy cost is based on the efficiencies in Table 3-3 and it is applied only for the EPRI specifications.

In Figure 3-1 data for Swedish car transportation are presented. The data is averages for years 1999 to 2001 and have been provided by SIKA. The X-axis represents the driving distance per day. The driving distance can be compared with the AER and using the curves in the figure the EDF can be found in the Y-axis. This implies that the charging of the PHEV will be done once during nights only. Two curves are presented. One is the cumulative average driving distance per day per car (called assumed EDF). The assumed EDF describes a car use where all daily trips that are longer than the AER will be run entirely on gasoline, which is a conservative case for the use of electricity. The other curve is called the potential EDF. This assumes that also the first part equal to the AER of the longer daily driving distances is powered by grid electricity.

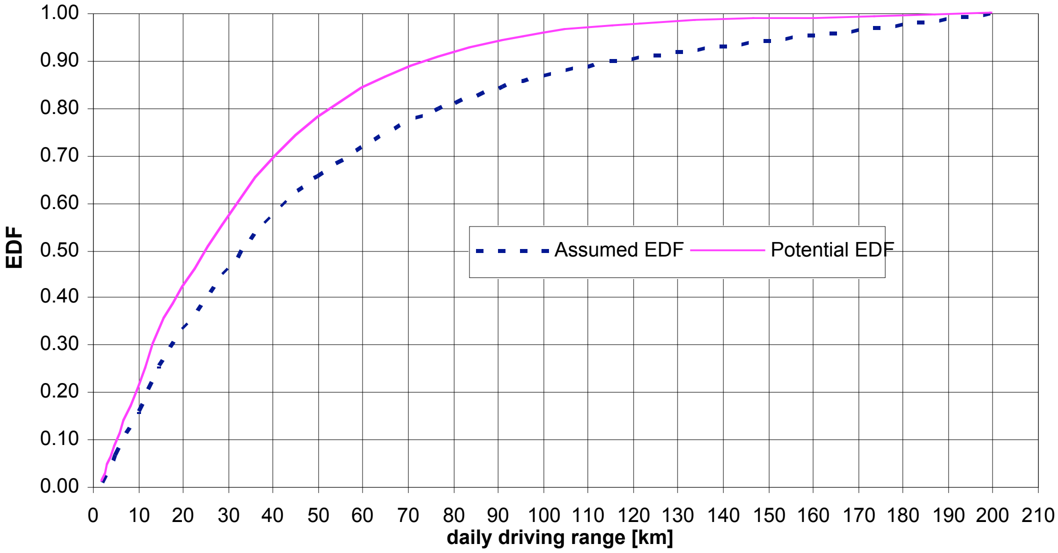


Figure 3-1 Cumulative average driving distance share per day per car in Sweden. For further explanation, see text. Averages for 1999 to 2001 (Data from Appendix D).

With the assumption that charging will be done only during nights there is for the single vehicle an upper limit of EDF for each AER. Nightly charging implies only one charge per driving day. Therefore the electricity driving fraction for a given annual driving distance for a vehicle will depend also on the annual number of driving days. Table 3-8 shows the maximum EDF for the AERs investigated in this study for different combinations of annual number of driving days and annual driving distance. A PHEV 20 could operate up till 73% of its annual driving distance in all-electric operation, while a PHEV 60 could operate totally on electricity. However a PHEV 20 or a PHEV 60 could also operate at significantly lower EDFs. The maximum EDF depends on the individual driving patterns. The assumed EDF of Figure 3-1 is used as base case for all three options, as a conservative case for electric operation. The effect of varying EDF is investigated in the sensitivity analysis.

Table 3-9 Maximum electricity driving fraction for different driving patterns.

AER [km]	Annual driving distance [km]	Number of days driving annually	Maximum electric driving [km]	Average driving distance per day [km]	Maximum EDF
32 (PHEV 20)	16 000	50	1 600	320	0.1
		200	6 400	80	0.4
		365	11 680	44	0.73
	32 000	50	1 600	640	0.05
		200	6 400	160	0.2
		365	11 680	88	0.37
64 (PHEV 40)	16 000	50	3 200	320	0.2
		200	12 800	80	0.8
		365	16 000	44	1
	32 000	50	3 200	640	0.1
		200	12 800	160	0.4
		365	23 360	88	0.73
96 (PHEV 60)	16 000	50	4 800	320	0.3
		200	19 200	80	1
		365	35 040	44	1
	32 000	50	4 800	640	0.15
		200	19 200	160	0.6
		365	35 040	88	1

Table 3-9 summarizes the EDFs that are used in this study. US mileage weighted probability (MWP), which is comparable to the EDF is also presented. The MWP is the annual electric driving fraction for the US which was obtained by EPRI (2001) using results of an US transportation survey. It must be noticed that US average annual driving distance is significantly higher than the Swedish average annual driving distance.

Table 3-10 Electricity driving fractions.

AER [km]	Sweden Assumed EDF[a]	Sweden Potential EDF[a]	Maximum EDF[b]	US low commute distance MWP[c]	US average commute distance MWP[c]	US high commute distance MWP[c]
32 (PHEV 20)	0.48	0.6	0.73	0.64	0.40	0.30
64 (PHEV 40)	0.74	0.85	1.46 (1)		0.60	
96 (PHEV 60)	0.86	0.95	2.19 (1)	0.76	0.74	0.72

[a] from Fig 3-1

[b] from Table 3-8

[c] The mileage weighted probability (MWP) for US has been derived from EPRI (2001).

The cost of energy per km is then calculated using the following formulas:

$$C_{gas,km} = p_{elec} EDF\left(\left(1 - F_{Hwy}\right)\left(Eff_{elec,city}\right) + \left(F_{Hwy}\right)\left(Eff_{elec,Hwy}\right)\right) \tag{5}$$

$$C_{elec,km} = p_{gas}\left(1 - EDF\right)\left(\left(1 - F_{Hwy}\right)\left(Eff_{gas,city}\right) + \left(F_{Hwy}\right)\left(Eff_{gas,Hwy}\right)\right) \tag{6}$$

$$C_{energy,km} = C_{elec,km} + C_{gas,km} \tag{7}$$

Here $C_{x,km}$, is the cost per km of energy category x, p_y is the price of energy carrier y, $Eff_{z,u}$ is the efficiency for the operation with energy category z, in the u driving mode, F_{Hwy} is the fraction of the driving that occurs in highways. Table 3-10 shows these factors for the US. In this study for Sweden it is used the US low driving commute distance $F_{Hwy} = 0.53$.

Table 3-11 Highway driving share (adapted from EPRI 2001).

Driving commute distance	Highway driving share F_{Hwy}
US Average	0.49
US low	0.53
US mid	0.47
US high	0.53

The calculation of the energy cost implies the setting of the control strategy to electric operation (while there is still energy in the battery).

3.3.2 Blended operation

The blended operation is based on NREL specifications (Table 3-4). The control strategy will basically tend to use the battery-motor combination at the limits, and use the engine as a supplement (Simpson 2006, p. 8). It is assumed that the fuel consumption and the electricity consumption occur at the same time. However it must be taken into account that for instance for the PHEV 20, using the data in Table 3-4 the electricity will last for first 100 km only, after that the vehicle would have to be driven in fuel only mode. This fuel only mode is not taken into account in the calculations. However this will happen only when the vehicle exceeds the blended operation range and this would not occur very often. Equation 8 is used to calculate the energy cost per km.

$$C_{energy,km} = p_{gas} Cons_{gas,km} + p_{elec} Cons_{elec,km} \tag{8}$$

Here $Cons_{x,km}$ is the consumption of the energy carrier x per km.

3.4 Total costs and savings

The total costs per km here include only capital costs and driving energy costs, other costs like maintenance and insurance are not considered. The total costs per km becomes

$$C_{total,km} = C_{capital,km} + C_{energy,km} \tag{9}$$

The total savings per km compared to CV is then

$$S_{km} = C_{total,km,X} - C_{total,km,CV} \tag{10}$$

Here S_{km} indicates the savings per km of using the vehicle Y compared to using the conventional vehicle *(CV)*.

It should be noticed that the method here assumes that prices of energy would be constant during the ten years, the time used for discounting of the retail price.

3.5 Total energy and CO2

The number of vehicles and the annual driving distance has been used for estimating the future energy use of the personal transport system. Table 3-12 gives average driving distance for years 2004 and our projections for 2010 and 2015.

Table 3-12 Projected cars and driving distances in Sweden.

Year	Population [a]	Number of cars	Average driving distance [km/vehicle]	Total distance [Gm]
2004	9 011 392	4 266 779 [b]	14 360 [c]	61271
2010	9 256 700	4 784 000 [d]	15 300 [e]	73195
2015	9 460 300	5 194 000 [f]	16 083 [g]	83535

[a] Statistics Sweden 2006
[b,c] SIKA 2005
[d, f] Bilsweden 2002
[e, g] Linear projection from data for year 1999 to 2004

For comparison, the US average driving distance is 21 315 km per year (EPRI 2001, p. C-12). This is considerably higher than Swedish average driving distance. The annual driving distance of the 27.5% lower commute driving households in the US is 12 339 km (EPRI 2001, p. C-13), which is slightly less than the Swedish average for 1999.

For estimating the energy use from the private car system, the following expression is used:

$$E_{total,Y,t} = n_t \times \left(E_{gas,Y,t} + E_{elec,Y,t}\right) \tag{11}$$

Here $E_{total,Y,t}$ is the total energy consumed in the year t when all the cars are of type Y, and n is the number of cars in the year t. $E_{z,Y,t}$ is the total energy used in the year t by the vehicle option Y using the energy carrier z. The energy content of one liter of gasoline is set to 8.8 kWh.

The following formula is used to estimate the annual emission of CO2 from a car.

$$CO2_{Y,x} = EF_{CO2-gas} \times Cons_{gas,Y,x} + EF_{CO2-elec-z} \times Cons_{elec,Y,x} \tag{12}$$

Here $CO2_{Y,x}$ is the total emission of carbon dioxide of the vehicle option Y in the year x, $EF_{CO2-gas}$ is the CO2 emission factor for gasoline per volume of gasoline consumed, and $EF_{CO2-elec-z}$ is the CO2 emission factor for electricity for the z electricity production technology. The CO2 emission factors used are shown in Table 3-13. $Cons_{z,Y,x}$ is the consumption of the energy carrier z by the vehicle Y in the year x.

Table 3-13 CO2 emission factors.

Gasoline	$EF_{CO2\text{-}gasoline}$	2357 gCO2/l [a]
Coal power electricity	$EF_{CO2\text{-}elec\text{-}coal}$	992 gCO2/kWh [b]
Carbon neutral electricity	$EF_{CO2\text{-}elec\text{-}neutral}$	0 gCO2/kWh
Swedish average electricity	$EF_{CO2\text{-}elec\text{-}sweden}$	25.6 gCO2/kWh [c]
Natural gas electricity	$EF_{CO2\text{-}elec\text{-}NG}$	406 gCO2/kWh [d]

[a] deduced from Swedish average 198 gCO2/km and 8.4 l/100km (Vägverket 2004)

[b] deduced from 275833 kgCO2 per TJ electricity derived from power plant (183000 kg hard coal input) (Frischknecht et al. cited in Baumann and Tillman 2003)

[c] estimated from Appendix F

[d] Using of 0.5 efficiency for generation of electricity from natural gas. Emission factor from Statistics Sweden n.d.

For estimating the biomass requirements in case of a personal car system based on the different vehicle options supplied by bioenergy only, Eq. 11 is used with efficiencies of 0.43 for electricity from biomass (assuming cogeneration plant with gasification and combined cycle), and 0.6 for production of biofuels from biomass (Johansson 1996).

3.6 The spreadsheet model

A spreadsheet model has been developed and used to perform all the calculations. The spreadsheet model facilitates easily vary some conditions like:

- Gasoline price
- Gasoline taxes
- Electricity price
- Electricity taxes
- Battery prices
- Discount rate
- Set of specifications and cost method
- EDF
- DOD

3.7 The base case

The base case has been defined as the following:

- 2004 prices and taxes of energy in Sweden, Table 3-14
- EPRI level of battery price
- 6% discount rate and 10 years lifetime for initial investment
- EPRI specifications of the vehicles
- EPRI method
- projected Swedish average driving distance for 2015
- EDF equal to Assumed EDF (Fig 3-1)
- a DOD of 80%

Table 3-14 Energy carriers prices.

Energy Carrier	Price (including tax)	Tax
Sweden 2004 Gasoline[a]	10.09 SEK/l	6.83 SEK/l
Sweden 2004 Domestic Electricity[b]	1.22 SEK/kWh	0.48 SEK/kWh
US 2004 Gasoline[c]	3.56 SEK/l	
US electricity[d]	0.65 SEK/kWh	

[a] Svenska Petroleum Institutet (2006)
[b] Swedish Energy Agency (2005)
[c] Energy Information Administration (2006)
[d] Markel and Simpson (2006)

In the calculations the used currency conversion is 8.3 SEK/USD, which is the average exchange rate from December 1996 to November 2006 (x-rates.com n.d.).

4 Results

In this chapter the results are presented. First the capital and driving energy costs are shown. Then the optimal vehicle option and the sensitivity analysis regarding savings compared to CV are presented. Finally, the estimate of car transportation total energy use and CO2 emissions are presented.

4.1 Costs

Figure 4-1 gives the retail prices for the eight vehicle options with different specifications and different cost methods. The EPRI specifications options share the same glider price. The NREL options share a glider with a higher price. See vehicle retail prices according to each method in Appendix C. The lowest price option is the CV, and all the hybrid options have higher costs. As the hybridization becomes higher, the cost increases. Differences in price according to different methods result in different incremental differences. As the incremental difference increase, the economic performance of hybridized options diminishes. The vehicles according to NREL specifications have significantly higher prices due mainly to the cost method and higher glider price. At long AERs higher battery capacity becomes important also (Section 3.1). Differences in specifications can be appreciated in section 3.1.

In the case of the three EVs, the one with the smallest battery is the one with the lowest cost, while the one with the longest range is the one with the highest cost for each cost method. The EV 60 and EV* are electric options with 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 and its higher cost compensates partially the engine cost. The EV 350 has the highest price of all the options, because of its high battery capacity and high power motor.

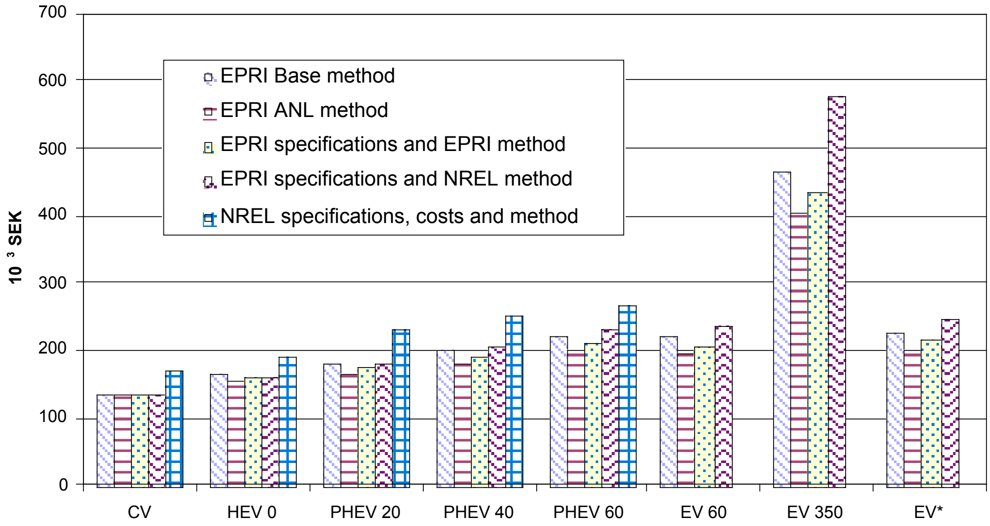


Figure 4-1 Retail price of vehicle options.

Table 4-1 shows the retail price difference of the PHEV 20 relative to CV and HEV 0 for EPRI specifications with both EPRI method and NREL method and for NREL specifications with NREL method. It can be noted that the incremental difference of the PHEV 20 to CV of NREL specifications with NREL method is around 50% higher than that with EPRI specifications and EPRI method. Also, the incremental difference of PHEV 20 to HEV 0 with NREL specifications and method is significantly higher (almost 3 times) the one of EPRI specifications and method. The decomposition shows that this PHEV 20 to HEV 0 retail price difference between NREL and EPRI is due to both differences in incremental vehicle specification as well as in the mark-ups (about 50 % due to each of them).

Table 4-1 Retail price difference between PHEV 20 and CV and HEV 0, respectively, for different vehicle specifications and cost methods [10^3 SEK].

Specification and cost method	Difference PHEV 20 – CV			Difference PHEV 20 – HEV 0		
	Total difference	Of which components	Of which mark-ups	Total	Of which components	Of which mark-ups
EPRI specifications and EPRI method	39.7	26.2	13.5	14.5	10.8	3.8
EPRI specifications and NREL method	45.6	26.2	19.4	18.7	10.8	8.0
NREL specifications and NREL method	60.1	34.5	25.5	39.3	22.6	16.7

Figure 4-2 shows the energy costs per km of all the eight vehicle options for both sets of specifications. The energy costs of the CVs are the highest of the shown options. The lowest are the energy cost of the EV*, which is an electric vehicle with a range of only 88 km and since it does not have a "big" battery and it does not have an ICE, it has the highest energy efficiency. As the AER becomes longer the driving cost becomes lower. The main reason is the increase in efficiency due to the increased use of electric traction. Another factor is that in Sweden electricity and gasoline have reasonably comparable prices on an energy basis. Regarding the difference in energy cost between EPRI and NREL specifications, it is evident that the EPRI options have always a lower energy cost for the same denomination vehicle. Energy cost is strongly related to performance. The NREL options demand more energy.

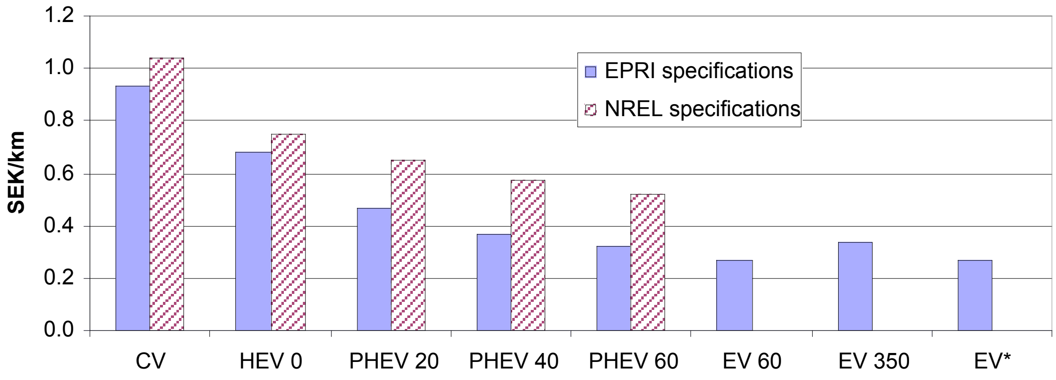


Figure 4-2 Energy costs for the different vehicle options.

Table 4-2 shows the savings in energy cost for each set of specifications when going to a PHEV 20 from a CV and a HEV 0, respectively. For the PHEV 20 – CV difference, EPRI specifications provide 20% higher savings than the NREL specifications. For the PHEV 20 – HEV 0 case, the EPRI specifications give twice higher energy savings compared to NREL. EPRI specifications imply significantly higher energy efficiency for the plug-in options.

Table 4-2 Savings in energy costs of PHEV 20 compared to CV and HEV 0 [SEK/km].

Specification	PHEV 20 – CV	PHEV 20 - HEV 0
EPRI specifications	0.46	0.21
NREL specifications	0.39	0.10

Figure 4-3 shows the total cost per km for all the vehicle options analyzed with EPRI specifications. The option with the lowest total cost is the PHEV 20 and the EV 350 has the highest. The second lowest cost is the EV 60. The third lowest option is the PHEV 40. It can be noticed that for the CV, the energy cost is a very significant part of the total cost. When hybridization increases, the energy cost turns less significant in comparison to the total cost.

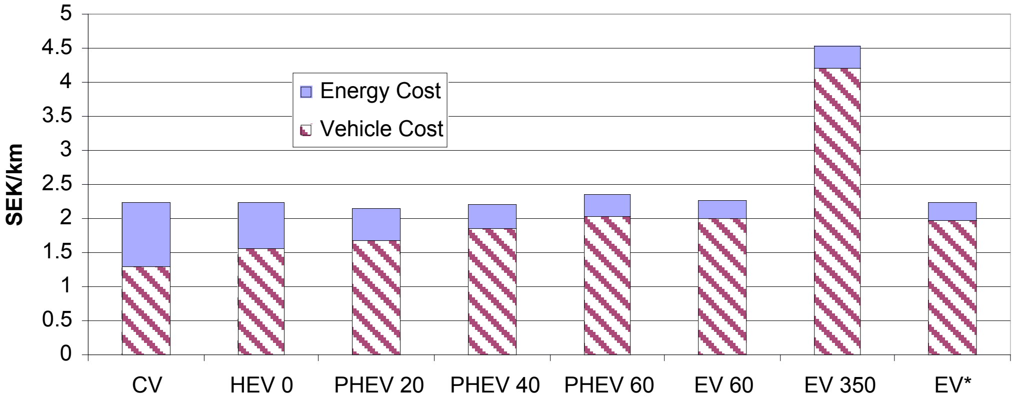


Figure 4-3 Total costs with EPRI specifications and EPRI cost method.

Figure 4-4 shows the total cost for NREL specifications with NREL cost method. The lowest cost vehicle is the HEV 0, followed by the CV. The plug-in options have higher total cost than the fuel-only options. Each NREL option has a higher total cost than its comparable EPRI option.

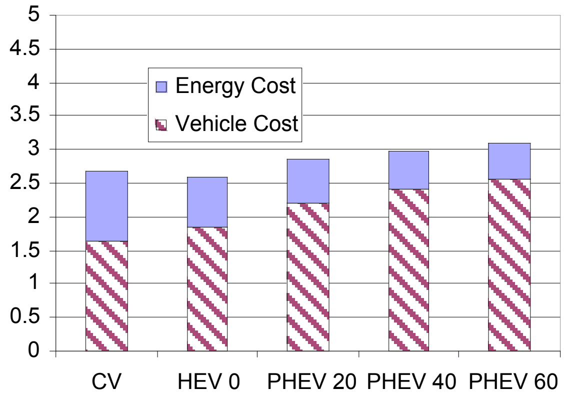


Figure 4-4 Total costs with NREL specifications and NREL cost method.

4.2 PHEVs savings

In this section an evaluation is performed of the hybrid vehicle options and their economic performance compared to conventional vehicles for the base case conditions. (The base case conditions can be found in section 3.7.) Figure 4-5 shows the savings in energy costs compared to the additional capital cost in relation to the CV. The line indicates the equality of the additional capital costs and the savings in energy costs. The HEV 0, PHEV 20 and PHEV 40 all offer positive net savings compared to CVs.

The EV 350, the electric car option with the same travel independence 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 is the lowering in efficiency due to the increase in mass with range. Electricity storage would have to lower their prices considerably to be able to have comparable long ranges with all-electric traction at reasonable costs.

The EV 60 operates at lower energy costs and has a somewhat lower capital cost than the PHEV 60. The EV 60 does not have the same utility, though, because it does not have the travel independence of the PHEV 60. Neither the EV 60 nor the PHEV 60 are economically viable options compared to CV.

Of the three electric options, the EV* is the only one with the same economic performance as the CV. However, the EV* utility as a vehicle is not the same. The EV* has a range of 88 km (55 US miles) compared to the CV's 560 km. Swedish conditions make all-electric vehicles a competitive option ignoring the short but still reasonable range. In fact electric cars with ranges below 88 km would give lower total cost per km in comparison to CV. Lower prices of electric traction components and further battery development would help the upcoming of short range EVs. The differences in operation costs between the EV 60 and EV* are very small, since they have similar energy efficiency.

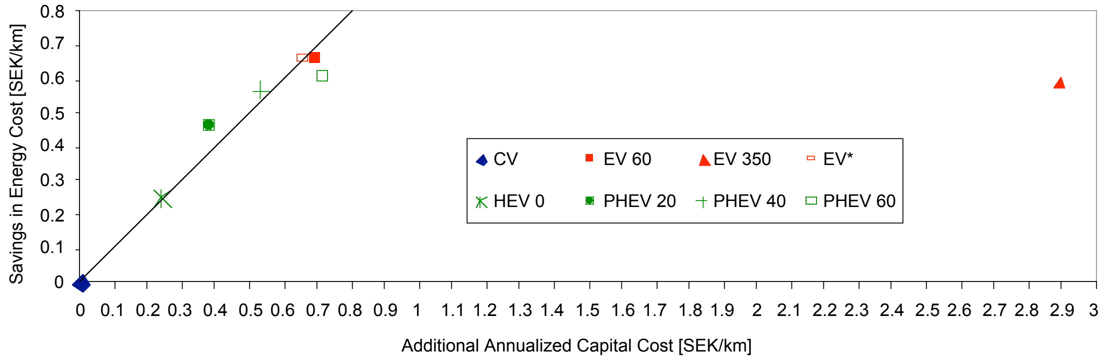


Figure 4-5 Vehicle option savings in driving costs vs. additional capital relative to the CV (base conditions).

In Figure 4-6 the savings of the HEV 0 and PHEVs compared to the CV are isolated. The savings per km of the different drivetrain options can be appreciated as positive bars. Vehicles with negative values have additional total costs, and are thus a less economically favorable option from the owner perspective. The optimal among the considered options is the PHEV 20, because it gives the highest savings. The savings of that option are around 0.10 SEK/km. It should be noticed that second and third vehicles in savings are the PHEV 40 and the HEV 0 respectively. This means that PHEVs of lower than around 40 km AER (or maybe a bit more) are more competitive than the HEV 0, CV and PHEVs with longer AERs for what has been defined as base conditions (section 3.7). The PHEV 60 has the worst economic performance of the presented options.

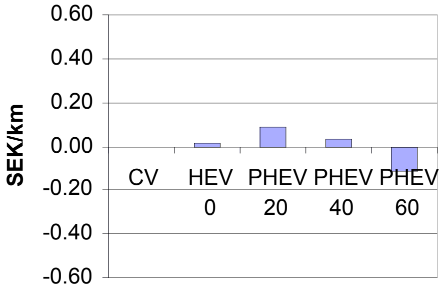


Figure 4-6 Savings in total costs compared to the CV with base conditions.

4.3 Sensitivity analysis

In this section we evaluate the sensitivity of the results for savings in total costs and optimal vehicle option when deviating from the base conditions.

4.3.1 Different specifications and cost methods

In Figure 4-7 the savings in total costs with EPRI specifications and NREL method and mark-ups are shown. PHEV 20 is still the optimal option; however the savings are lower than in the base case. In fact the cost savings relative to the CV of all the PHEV options decreases. The main reason for the difference in results is the way of calculating the mark-ups for batteries. In the EPRI method, the mark-ups of batteries are almost independent of size and they are not a big part of the battery price for the longer-range options. In the NREL cost method, mark-ups of batteries are treated as every other mark-up and is proportional to the battery manufacturing cost (see section 3.2.2).

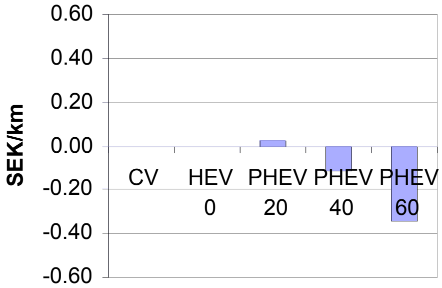


Figure 4-7 Savings in total costs relative to the CV with EPRI specifications and with NREL cost method.

In Figure 4-8 the results with NREL specifications (higher performance, blended operation, SOC window for 15 years battery life) and NREL cost method are shown. The optimal option is the HEV 0. PHEVs are not cost-effective with these specifications. The main reason of these differences is that in the EPRI case savings in energy and capital costs related to plug-in capacity are much higher than those of NREL (See section 4.1). (For differences in specifications see Section 3.1 and for differences in retail price calculation method see Section 3.2.2.)

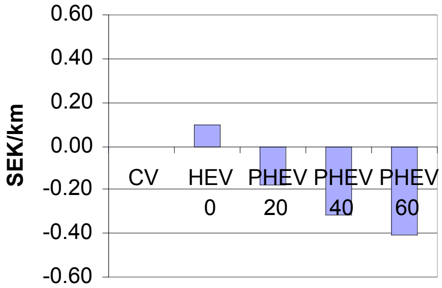
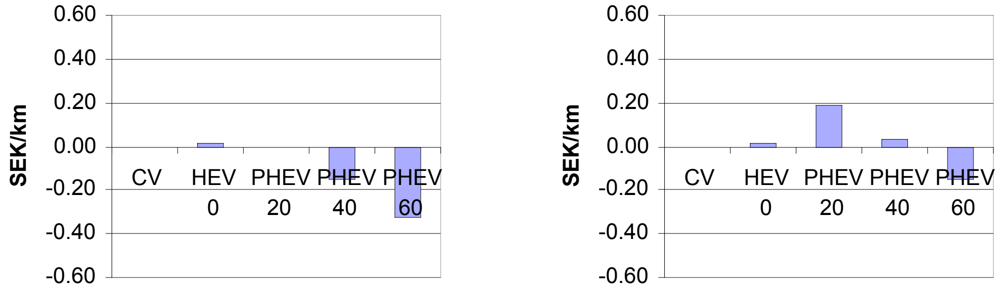


Figure 4-8 Savings in total costs relative to the CV with NREL specifications and with NREL cost method.

4.3.2 EDF

In Figure 4-9 the total cost savings when all the PHEVs would have the same EDF is presented. An EDF of 0.25 and 0.75 are used as extreme cases of electric driving. As it could be expected, the PHEV with the lowest capital cost (smallest battery) is the optimal option for high EDF. For the low EDF the economics of hybrid vehicles are such that the HEV 0 is the optimal option, however its savings compared to PHEV 20 and the CV are not significant. The PHEV 20 and the CV have similar economic performance.



a) b)

Figure 4-9 Savings in total costs relative to the CV with a) EDF = 0.25, b) EDF = 0,75.

In Figure 4-10, the potential EDF in Figure 3-1 and Table 3-9 is used. With this higher EDF for each AER, the PHEV 20 is still the optimal. The PHEV 40 has a higher economic performance than in the base case. In general higher EDF increases the benefits of plug-ins.

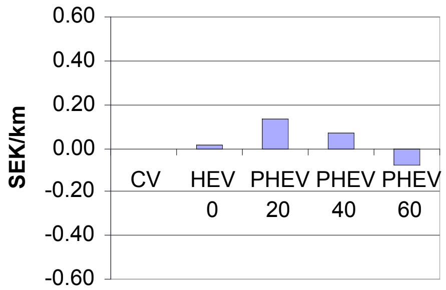
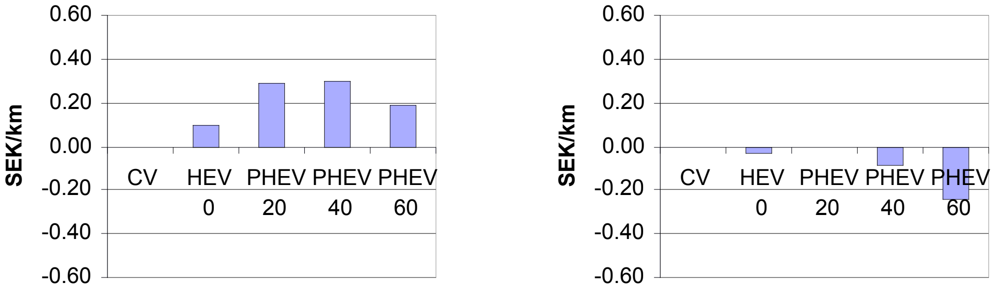


Figure 4-10 Savings in total costs relative to the CV with potential EDF.

4.3.3 Gasoline prices and taxes

The price of gasoline in 2004, only including product cost and gross marginal (*Bruttomarginal*), was 3.26 SEK/l. With doubled and halved this price, respectively, different PHEV options are optimal, Figure 4-11. The PHEV 40 is the optimal for the high price of gasoline case. The PHEV 20 reaches cost neutrality with CV, and all the other options have lower economic performance for the low gasoline price.



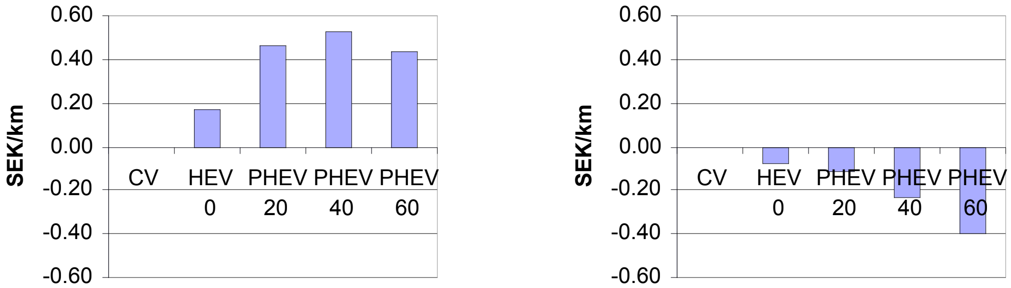
a) b)

Figure 4-11 Savings in total costs relative to the CV with a gasoline price of a) 6.8 SEK/l, b) 1.7 SEK/l (200% and 50% of base case, respectively).

In 2004, taxes on gasoline were 6.83 SEK/l, which were 68% of the total pump price. The high and low cases for taxes are set to 13.6 SEK/l and 3.4 SEK/l. The case for high taxes is similar to the case with high gasoline price, although with different magnitude, Figure 4-12. The low tax case shows a big change, there is no better option than the CV. The results with no taxes on gasoline are presented in the Figure 4-13. With no taxes PHEVs would not be a viable option.

Figures 4-12b and 4-13 show that Swedish level of taxes on gasoline is very significant regarding cost effectiveness of hybrid options. An important observation is that with no taxes, even the HEV 0 is not more cost efficient than the CV option. With a low pump price of fuel the extra costs of hybrid drivetrain and energy storage overpass the energy cost benefits.

It must be taken into account that when prices of gasoline go down, the last hybrid option in becoming non cost effective is the PHEV 20. A further analysis has been made with the rest of conditions kept as the base case for calculating the lowest price of gasoline at which the PHEV 20 is optimal. Neutrality of PHEV 20 with CV occurs at a price of gasoline of around 8,5 SEK/l (including taxes). Below that price, PHEVs are no longer a cost efficient option. High fuel prices or high taxes make PHEVs in general a good option. In fact with high taxes or price, the PHEV 40 becomes the optimal option.



a) b)

Figure 4-12 Savings in total costs relative to the CV with gasoline taxes equal to a) 13.6 SEK/l b) 3.4 SEK/l (200% and 50% of base case, respectively).

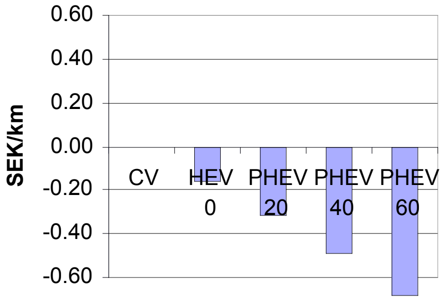
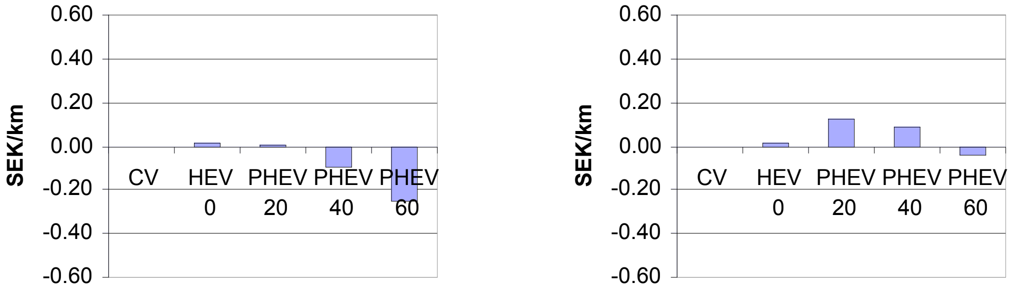


Figure 4-13 Savings in total costs relative to the CV with no taxes in gasoline.

4.3.4 Electricity prices and taxes

In 2004 the total domestic price of electricity (including taxes, distribution net cost, and green certificate fees) was 1.21 SEK/kWh. The price of electricity without the taxes was 0.76 SEK/kWh. In Figure 4-14, the effect of doubled and halved price for electricity (without taxes) is shown. Even for price of electricity of 1.52 SEK/kWh, the PHEV 20 is still better than CVs, although with lower savings than those of base conditions. The optimal option is the HEV 0 by a small margin. In the low price case (Fig. 4-14b), the PHEVs have a better performance than with base case electricity price; however the HEV 20 is still the optimal option.



a) b)

Figure 4-14 Savings in total costs relative to the CV with an electricity price of a) 1.52 SEK/kWh, b) 0.38 SEK/kWh (200% and 50% of base case, respectively).

The taxes for domestic electricity were 0.48 SEK/kWh, which is 39% of the total price. In Figure 4-15 we present the effect of doubled and halved taxes on electricity, respectively. As expected this result is very similar to that of changed price of electricity, only with different magnitude. PHEV viability is not as sensitive to the electricity price as it is for the gasoline price. However, lower price of electricity will increase the savings of all the plug-in options. PHEV 20 is still optimal under the varied conditions.

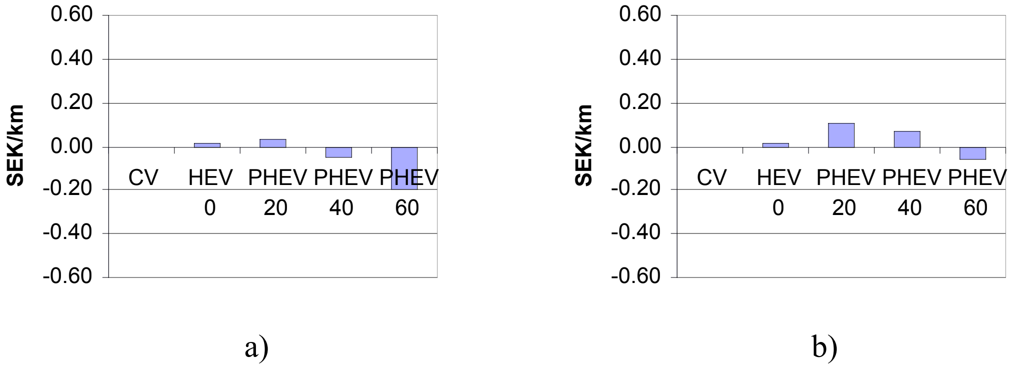


Figure 4-15 Savings in total costs relative to the CV with electricity taxes of a) 0.96 SEK/kWh, b) 0.24 SEK/kWh (200% and 50% of base case, respectively).

4.3.5 Battery prices

The battery costs obtained with the cost function (see section 3.3.1) have been multiplied to estimate a higher or lower price of battery. For high prices the factor 1.5 has been assumed and for low prices, 0.5. Results are presented in Figure 4-16. As expected, the PHEVs with longer all-electric ranges show a lower economic performance with higher prices for batteries and vice versa. In fact with high battery price, the PHEV 20 is the only option with savings. For the low price of batteries all the hybrid options provide savings, and the optimal is now the PHEV 40. The battery price is an important factor regarding PHEV in general; however under the assumed conditions, the PHEV 20 is profitable compared to both the CV and the HEV 0 for both cases of battery prices. Battery prices would have to be more than twice the EPRI forecasted prices to make the PHEV 20 have negative savings.

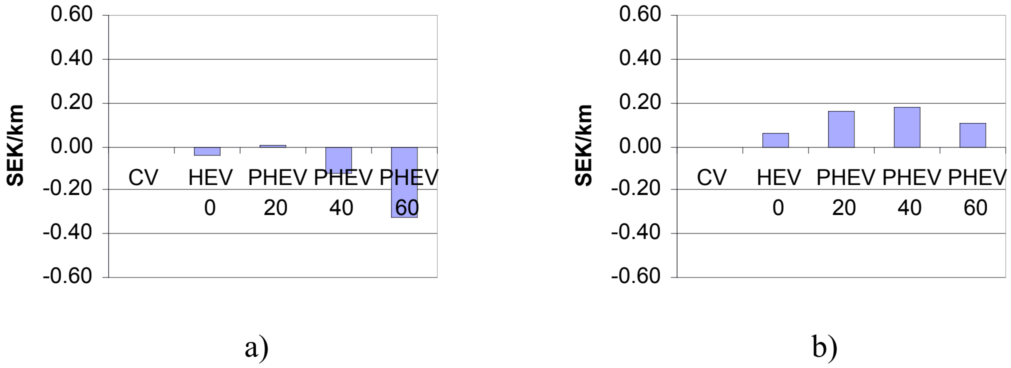
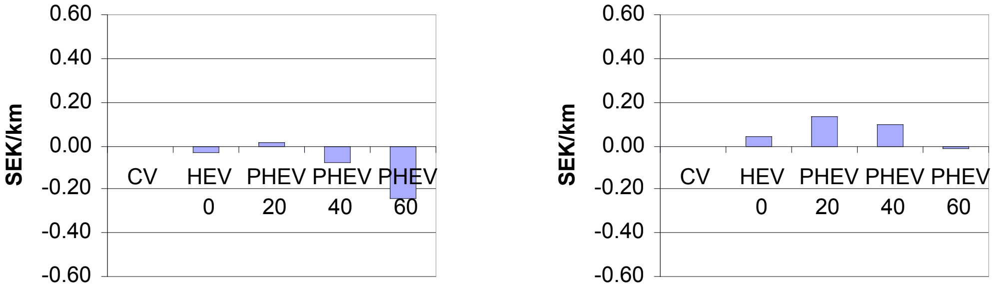


Figure 4-16 Savings in total costs relative to the CV with battery price equal to a) 1.5 times, b) 0.5 times, respectively, of the base case price.

4.3.6 Discount rate

A discount rate of 6% is commonly used in Sweden in economic evaluations for risk free investment. The discount rate has been varied though, using 10% as a high and 3% as a low value, Figure 4-17. Low discount rates benefit the higher price options, that is, the vehicles with longer AERs. In the high discount rate case, the only option with positive savings is the PHEV 20. In both cases the PHEV 20 is still the most cost efficient option.



a) b)

Figure 4-17 Savings in total costs relative to the CV with the discount rate set to a) 10%, b) 3%.

4.3.7 DOD

According to Markel and Simpson (2006), a NiMH battery should be used at maximum 70% DOD for having a cycle life of 4000 cycles, which with one cycle per day would be around 11 years. The savings for a lower DOD of 50% is depicted in Figure 4-18. It should be noticed, that this results might not be accurate for longer AERs, because this variation increases the mass of the batteries and the vehicles, with 5%, 7%, 9% and 14%, for the HEV 0 and PHEV 20, PHEV 40 and PHEV 60, respectively. A lowering of the vehicle efficiency due to any increase in mass has not been taking into account. However, for the PHEV 20, the increase in mass does not seem to be significant, and this is the option that seems to be interesting for Sweden.

DOD is significant regarding capital cost. Lower DODs require bigger batteries, and therefore imply higher capital cost. Even with a very low DOD, the PHEV 20 is still the optimal, though (Figure 4-18). The implications of this are very important, because it means that if, for small AER, the DOD would have to be as low as 50% for protecting the battery life, the PHEV 20 is still the optimal option. It should be noted though, that a DOD of 50% is extremely low for the NiMH chemistry.

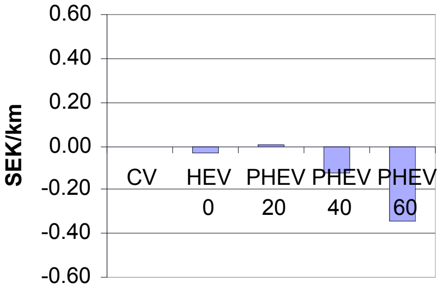


Figure 4-18 Savings in total costs relative to the CV with 50% DOD.

4.3.8 US conditions

Using the US conditions for the year 2004, with pump prices of 1.85 USD/US gallon (3.56 SEK/l) and electricity prices of 0.09 USD/kWh (0.65 SEK/kWh) (Energy

Information Administration 2006, Simpson 2006), as well as average driving distance and patterns for the US, results in savings according to Figure 4-19. With US conditions the CV is the most cost efficient option, similar to the situation for Sweden with low taxes on gasoline.

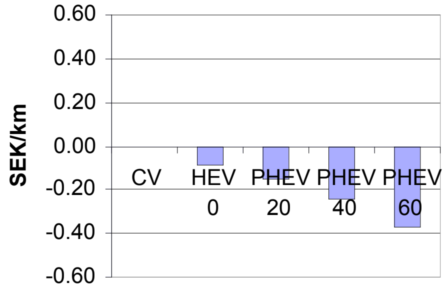


Figure 4-19 Savings in total costs relative to the CV for US conditions.

Assuming the expected future price of gasoline by Markel and Simpson (2006) of 4 USD/gallon (7.61 SEK/l), and the same price of electricity as used above, we will get the savings presented in Figure 4-20. In this case, with relatively high pump prices, the PHEV 20 has the best economic performance.

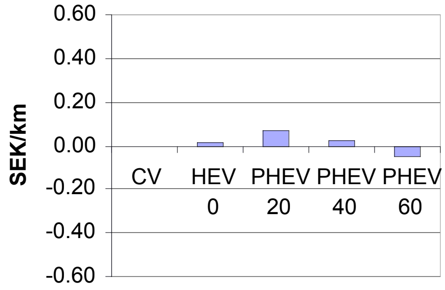


Figure 4-20 Savings in total costs relative to the CV for US conditions but now with a price of gasoline of 4 USD/gallon (7.61 SEK/l).

4.3.9 Summary of sensitivity

In the sensitivity analysis we have found that PHEVs are economically viable for the user under a wide range of conditions. However, we have shown that PHEVs are not viable, specifically when

- NREL specifications and NREL cost method are used
- low (or no) taxes on gasoline prevails

(US conditions are not taken into account here. It is considered that PHEVs are viable when none of the PHEV options is optimal.) It is important to notice that NREL specifications are based on a higher performance car with blended operation (see 3.1). For a description and implications of the NREL cost method see 3.2.2 and 4.1.

Low taxes on gasoline are the other main condition for non-viability of PHEVs. PHEVs are not viable with a gasoline pump price (fuel and tax) lower than 8,5 SEK/l. Accepting the performance of the EPRI vehicles implies that low pump price is the only condition for non-viability of PHEVs.

Of the different PHEVs investigated here, the PHEV 20 is the optimal option for most conditions. The following list gives the conditions for which the PHEV 20 is not optimal, though:

- NREL specifications and NREL cost method
- Low (or no) taxes on gasoline
- High gasoline prices or taxes
- Low prices of batteries

Under conditions for which any PHEV are viable but the PHEV 20 is not the optimal one (i.e., the last two conditions in the list above), the optimal is the next in AER, the PHEV 40. In these cases, the PHEV 20 has still a better economic performance than both the CV and the HEV 0, though.

4.4 Total energy and CO2 emissions

In this section we analyze the implications for the Swedish energy sector of a large scale introduction of PHEVs. The EPRI CV (EPRI 2001) has roughly the same fuel economy as the average car sold in Sweden 2002 (SIKA 2005). With this fuel efficiency, the energy consumption by the personal cars system in 2004 would have been around 50 TWh.

As an illustration, Figure 4-21 gives the vehicle energy requirements for the different vehicle options (base case), each fulfilling the here estimated car transport demand of Sweden in year 2015. When using CV, the energy requirements would be around 68 TWh/year, but with a PHEV 20 based system, the energy demand could be around half of that. The electricity demands for the PHEV 20 based system would be around 9 TWh/year and for the PHEV 60, around 16 TWh/year, which is around 6 and 11 %, respectively, of the current Swedish electricity production and use (Swedish Energy Agency 2005a).

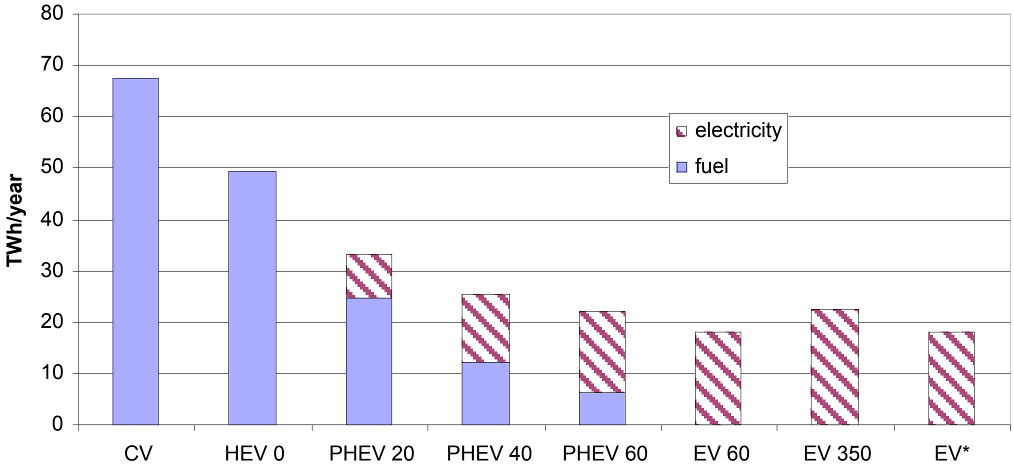


Figure 4-21 Total energy requirements of the personal car transport system relying totally on each of the vehicle option, respectively. Own projections of number of personal vehicles and driving distance for year 2015.

Assuming an EDF of 1 for each PHEV option gives an upper limit for electricity demand for plug-ins. The electricity (total energy) use would be around 18 TWh of or around 12% of the electricity production and use (Swedish Energy Agency 2005a). In fact, this is the electricity demand of every option that can operate entirely on electricity (PHEVs and EVs) (Figure 4-21).

The CO2 emissions of a system based on PHEVs are very dependent on the carbon intensity of electricity production supplying the vehicles. In Figure 4-22 four different assumptions on the electricity supply are illustrated: carbon neutral power, current Swedish average power, natural gas power and coal condensing power. The figures are based on base case EDF; a higher EDF would result in higher CO2 emission in the coal power scenario and lower emissions in the carbon neutral electricity scenario.

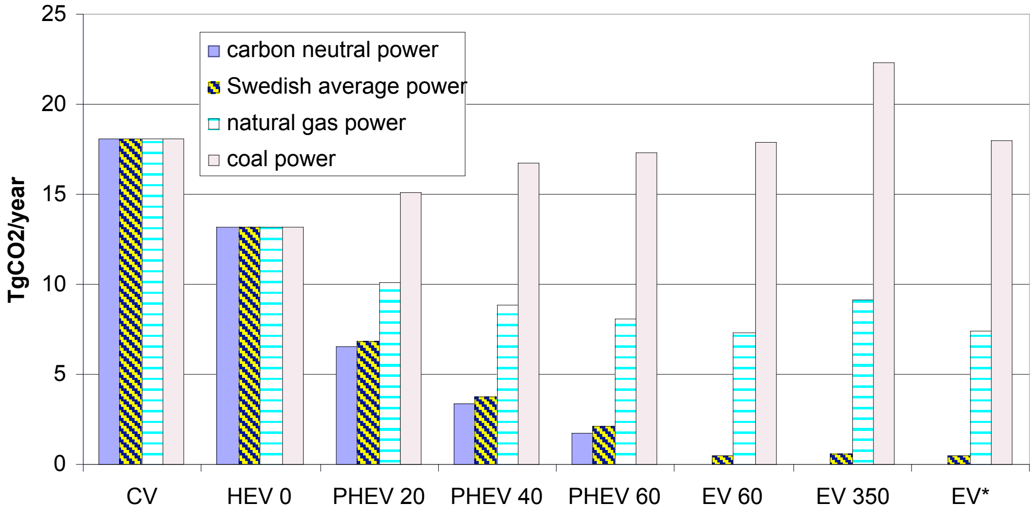


Figure 4-22 Projection of CO2 emission from the private car transport system relying on each of the different vehicle options, respectively. Three different electricity supply system assumed.

Although the CO2 emissions are very dependent on the electricity supply, the plug-in options have lower CO2 emission than the CV option in all cases, when the fuel is assumed to be gasoline. In 2015, a personal transport system based on CVs would emit around 18 Tg CO2, while a system based on PHEV 20 with carbon neutral power would emit 7 Tg CO2, with coal power 15 Tg CO2, with natural gas power 10 Tg CO2 and with Swedish average power 7 Tg CO2.

With electricity from coal condensing power there is an increase in CO2 emissions when going to plug-ins from HEVs and when increasing the AER, that is, the carbon savings compared to CVs come only from the hybridization of the car. In fact with coal power, the system based on HEV 0 would have the lowest emission with 13 Tg CO2, a PHEV 60 system would emit around 17 Tg CO2, only 1 Tg CO2 less than a CV system and long-range EVs even more than CVs. The EV emission would be similar to that of PHEVs with an EDF of 1.

The use of natural gas for electricity production gives always an intermediate case between carbon neutral and coal power. In the natural gas electricity case (as in the carbon neutral and Swedish average power) there is always a reduction of CO2 emissions when the DOH increases.

5 Discussion

The discussion in this chapter first deals with the limitation and significance of the results. Secondly a brief discussion about the availability of energy in Sweden for covering the demands of plug-ins is performed. Finally some implications of the use of the two different sets of performance and specifications are discussed.

5.1 Limitations and significance of results

In EPRI (2001) is stated that "the model validation is of utmost importance in any modeling study and real hardware should be built and tested to validate this study's result". 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. The results regarding economic performance are strongly dependent on vehicle price and efficiency. Significantly higher prices of electric traction components would lower the economic performance of hybrid options. In this point is important to notice that both main references, EPRI (2001) and NREL (Simpson 2006), share the main cost functions for components for future production of 100000 units per year (Section 3.2.1). The most important cost in electric traction is energy storage and both references accept the used cost function for this component as valid.

The results of this study depend strongly of the level or mark-ups. Three different methods of including the mark-ups for accounting manufacturing (assembly) and dealer costs and profits have been used with different mark-ups (see section 3.2.2). The mark-ups used are developed for US car manufacturers and dealers. It is known that levels of taxation and income wages are different between US and Sweden. Higher levels of taxation could suggest the use of different mark-ups for Sweden. Mark-ups have not been investigated in the Swedish context. The adjustment of precise mark-ups for Sweden (if required) has not been performed in this study. Electric traction components costs are very important in the incremental difference of the capital cost of hybrid options compared to CV. A higher level of mark-ups would increase the incremental difference of hybridized options compared to CV, resulting in a lower than estimated economic performance.

The total cost does not consider maintenance and insurance. In EPRI (2001) is stated that "Maintenance issues and costs should be reexamined in future studies, as more data on EV and HEV maintenance become available". However, it appears that maintenance would increase the savings with increasing hybridization (EPRI 2001), because maintenance of electric traction components would have lower costs than engine traction maintenance, and the electric traction would be used more than the engine traction. This is valid for EPRI specifications which are optimized for all-electric operation and have lower engine size as the AER increases (See Table 3-3). The inclusion of maintenance cost with EPRI specifications would increase even more the performance of PHEVs related to CVs. On the other hand NREL specifications are optimized for blended operation and have a lowest limit size of engine power of 80 kW (Simpson 2006), and DOH never overpasses 35%. With NREL specifications it is not certain that addition of maintenance cost would increase the economic performance of plug-in options. However, it should be noticed that the results show that NREL PHEVs are not cost-effective even without considering maintenance.

Policy incentives for environmental friendly cars have not been taken into account. Owners of PHEVs could receive tax discounts and discounts on parking fees. The inclusion of this type of incentive would increase the economic performance of PHEVs.

In the study only AERs of 32, 64 and 96 km are considered, and the sensitivity analysis gives the PHEV with the lowest AER as optimal under most of the conditions. The inclusion of a even shorter range might have produced a different optimal range under some conditions. However it is considered that a reasonably long AER is desirable for other reasons like energy savings and CO2 emission reduction of highly hybridized options (see section 4.3).

The results are based on modeling of vehicles based on current typical construction and aerodynamics of a US midsize sedan. The use of light weight materials and construction and better aerodynamics has not been considered. Such measures would increase the capital cost and lower the energy cost for each vehicle option (EPRI 2001). The difference in capital cost of hybrid options compared to CV could decrease also because of the lower battery capacity requirement (EPRI 2001). The use of advanced materials and better aerodynamics would enhance the vehicle performance of all the vehicle options.

The calculations of the electricity and fuel use assume that PHEVs with EPRI specifications use electricity only during the first part of the driving distance up to the AER (Section 3.3.1). However, if the control strategy of the traction is not set to forced all-electric operation, during small periods of high performance demands (for instance sudden accelerations) PHEVs would work in blended operation (even with EPRI specifications). During this periods some fuel would be used, which is not taken into account. This additional fuel use would decrease the economic performance of the PHEVs. The extra use of fuel would imply more use of energy and probably also additional emission of CO2 and other pollutants.

5.2 Plug-ins and energy in Sweden

Large scale introduction of PHEVs would imply the use of less total energy in personal transportation and an additional load to the electricity system (Figure 4-22). It should be noticed that the extended electricity demand depends strongly on the EDF, but the upper limit for PHEV 20 vehicles is 18 TWh/year . This figure is based on projection of average annual driving distance in Sweden in 2015.

The Swedish domestic electricity production is currently heavily dominated by hydro power and nuclear energy and includes also some wind and biopower. It has thus currently a comparably very low average CO2 intensity. However, well integrated into the Nordic and also north European electricity system, it is commonly affirmed that the marginal electricity is condensing power from fossil coal. The use of coal power would imply higher CO2 emissions from the private vehicle system (Fig. 4-22).

The additional electricity demand will probably mostly be fulfilled by nightly charging which could utilize off-peak capacity and contribute to a leveling out of the daily load variations. In Sweden in 2005 there were around 10 TWh less load during the eight hours between 22h00 and 6h00 (Appendix F.). Charging time for a PHEV 20 would take around 6 hours (Appendix G). There might thus be enough capacity for covering the electricity demands of a system based on PHEV 20 with the base case EDF. However the non-used installed capacity might be more carbon intensive than the average Swedish electricity. It must also be realized that water in the reservoirs is finite. The use of more hydropower in the night might also mean that less hydropower will be available during daytime. More additional power would be needed during daytime also.

Also, a considerable expansion of carbon neutral power capacity is being decided or planned in Sweden. Nuclear power upgrading will increase the installed capacity with over 1200 MW till 2012 (Eriksson 2005). Using a load factor of 0.8, this will increase the supply 7.5 TWh/year. Decided Green Certificates will add 17 TWh/year of carbon neutral power from year 2002 till year 2016 (Swedish Energy Agency 2005b). Therefore, it is likely that around 25 TWh/year of additional carbon neutral power will be produced in Sweden in the year 2016.

Additionally, PHEVs in combination with high pump prices can also provide incentives for further development of other carbon-neutral electricity generation technologies, like wind and power from bioenergy, for instance, in combined heat and power plants. With the Swedish price of gasoline in 2004, a PHEV 20 could afford paying more than 2 SEK/kWh and still have the same cost per km as a CV. Part of this margin could be used to pay for green certificates, increasing the possibility of building additional carbon-neutral power capacity.

Technically all the energy could be supplied from biomass. It is then also important to consider the domestic biomass production capacity. With the projections for year 2015, the biomass requirements for a personal car system based on CVs would be 113 Twh. With PHEV 20 vehicles the biomass requirements would be around 61 TWh (based on base case EDF). A system based on HEVs would require around 82 TWh/year. It should be noticed that if co-generation is utilized in the production of electricity, the cogeneration plants would produce heat besides electricity. The heat can be used outside the transportation system. In Sweden, the potentials of additional domestic bioenergy are higher than 100 TWh/year (Berndes and Magnusson 2006, Johansson 1996). There could thus in the future be enough biomass available domestically to cover the demands for a system based on PHEVs. This would imply a carbon-neutral private mobility system (considering use phase only) without the need for advanced technologies like fuel cell vehicles with carbon-neutrally derived hydrogen, which are not expected to become a commercial reality before the end of the next decade. The figures here are based on the use of biopower and biofuels. With a different perspective biomass could be used only for biofuels and the electricity demand could be covered by other carbon-neutral electricity sources (not necessarily biomass). In this case the demand of biomass would be only around 40 TWh (base case EDF) from a PHEV 20 based system.

5.3 Vehicle performance and specifications

In this study two different sets of specifications have been evaluated, NREL and EPRI. For the main analysis the EPRI vehicle specifications and cost method have been set as the base case conditions. The sensitivity analysis shows that NREL specifications with NREL cost method are not favorable for PHEV options (Section 4.2.1.1). NREL specifications vehicles have higher performance, due to a higher power to mass ratio. The use of EPRI vehicle specifications as base case implies the acceptance of the associated performance.

It is important to notice that both sets of vehicle specifications achieve energy savings and lowering in carbon emissions compared to the CV. However the lower performance EPRI vehicle uses less energy and more electric traction. Blended operation implies always using fuel; therefore the carbon savings have a lowest limit depending on the engine fuel efficiency. With all-electric operation, reasonably high EDF, and low carbon intensive electricity, the reduction in CO2 emissions compared to blended operation can be significant. Therefore the carbon intensity of the electricity supply for the plug-ins is very important when discussing design criteria or specifications related to the focus on blended operation or AER. In electricity systems with high shares of fossil power the climate benefits would not be significantly different with blended or all-electric operation. Swedish electricity is low in carbon intensity compared to the OECD European average and other OECD countries. Further carbon-neutral capacity expansion is planned. Taking into account greenhouse gas emissions, Sweden would have significantly higher incentives for PHEVs with all-electric operation.

In systems with high share of fossil power in electricity supply, from a technical perspective it seems currently easier to mitigate CO2 emissions from fossil stationary power plants than from mobile sources (like vehicles). New stationary coal-fired power plants could be upgraded with CO2 sequestration technology. Therefore using electricity might turn into a technically feasible way to use fossil fuels in transportation with no or low CO2 emissions. Therefore the all-electric operation could have favorable arguments regarding CO2 emissions even in systems with high shares of fossil power.

Performance is important when considering customer preference. The power to mass ratio is an important indicator of performance for vehicles. The power to mass ratio of NREL PHEVs is significantly higher than EPRI case PHEVs. Performance of NREL PHEVs is supposed to meet its base CV thus less energy use can only be achieved through a higher efficiency (Simpson 2006). On the other hand some trade-offs between performance and costs have been made in the EPRI case PHEVs to bring about all-electric operation at reasonable costs (EPRI 2001). As a result the savings achieved in the EPRI case are significantly higher than the NREL case savings, both in capital and energy cost (see Tables 4-1 and 4-2). Furthermore EPRI and NREL PHEVs could be seen as different perceptions of what a plug-in is. The NREL PHEV with its blended operation can be seen as a conventional fuel car with an efficiency-enhancing electric hybrid system where the plug-in possibility can make further contributions to fuel efficiency. The EPRI PHEV car is more easily perceived as an electric vehicle (and thus immanent efficient) with a range-enhancing kit (possibly compromising the efficiency somewhat, though).

Performance of PHEVs with AER is not necessary unacceptable in every category. In fact there are performance categories like acceleration from zero to mid range speeds in which EPRI PHEVs would overpass its base CV (Table 3-2). On the other hand, EPRI case PHEVs' top sustained speed is considerably lower than that of CV or HEV 0 (Table 3-2). However even the EPRI PHEV top speed is significantly higher than the highway speed limits in countries with speed limits, like Sweden. Engine technology seems to require high power rates to achieve comfortable acceleration from zero to mid range speeds. High power rates for achieving comfortable acceleration and low aerodynamic drag for fuel savings have implied high top speeds, which now seem strongly incorporated in the customer preferences. The upcoming of vehicles with electric traction (at least partial) should be accompanied by a change in car performance perception.

It can be noted that the newly by GM launched plug-in concept car, Chevrolet Volt, includes a series hybrid drivetrain (all-electric operation) with a relatively small engine working as a generator only for maintaining charge for range extension. GM claims that no trade-offs in performance would be needed (section 2.3.1). The vehicle included advanced light weight materials in its construction, which would help lowering the mass of the vehicle. This is maybe 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. Light weight construction and use of composite materials would probably include higher costs, at least in an introductory phase, though.

Regarding the results of this study, it is important to realize why the PHEV 20 with all-electric operation provides the highest savings. Capital costs and energy carriers' prices would not give the complete answer, since in Sweden energy as electricity is a bit more expensive than the same amount of energy as gasoline, and all electric operation also requires additional capital cost (battery-motor combination). Instead it is the high efficiency of the electric traction what makes PHEVs with reasonable AERs and EDFs a better option than CVs under high pump prices, even with the additional capital cost and in some cases with high prices of electricity. At the level of Swedish energy carrier prices it is significantly less expensive to use only electricity in driving considering only energy cost.

Additional modeling of hybrid vehicles according to preferred performance demands by Swedish potential car buyers could help illuminate with higher accuracy the real potential benefits of PHEVs without changes in performance demands. Acceptance of hybridized vehicle performance by Swedish buyers is not investigated in this study. However it must be considered that if people are able to accept a reasonably comfortable performance, the improvements in energy efficiency and CO2 emissions of using PHEVs with all-electric operation in a low carbon intensive electricity system could become a reality.

6 Conclusions

This study has presented an evaluation of the viability of PHEVs with three different AERs compared to CVs. HEVs and EVs have also been considered. The basis for evaluation has been the comparison of economic performance, energy efficiency and CO2 emissions. The economic evaluation has considered lifetime costs related to driving energy and capital and has included a sensitivity analysis for determining important conditions for viability. Capital costs are based on estimates of vehicle retail prices for a level of production of components of 100000 units per year with technical advantages expected for year 2010. Base case vehicle specifications are based on EPRI (2001). The EPRI specifications include trade offs between costs and performance and are optimized for all-electric operation. As a base case we have used Swedish energy carriers' prices in 2004, projected average driving distance for year 2015, and estimated average EDF for the years 1999 – 2001 in Sweden. Alternative specifications by NREL have also been used in the sensitivity analysis. NREL specifications assume a higher performance of the car and are designed for blended operation.

The results indicate that the vehicle specifications are very important for the outcome. PHEVs are a viable option compared to the CV and HEV 0 under main Swedish conditions with EPRI specifications. Beyond specifications it was found that the most important condition for the viability of the plug-ins is the high pump price.

The optimal AER of the ones assessed (32, 64 and 96 km) for Swedish conditions is 32 km. For current range requirements or preferences, PHEVs have better economic performance than total electric vehicles. Only EVs of total ranges similar to (or lower than) the AERs of the plug-ins could have better economic performance.

An introduction of PHEVs in the Swedish transportation system would imply energy savings in the transportation sector, due to the higher efficiency of the grid-supplied electric traction. The reduction in energy consumption will depend on the share of the PHEVs in the vehicle fleet and the electric driving fraction. With a large scale introduction of PHEVs the energy used in the personal transport system could be around 50% of that required by a pure conventional vehicle fleet. This energy demand is within the additional domestic bioenergy supply potential.

The reduction of CO2 emissions by replacement of CVs with PHEVs could be significant, if the used electricity has low carbon intensity. Planned expansion of carbon neutral capacity in Sweden (additional to its already low carbon intensive electricity system) gives good prospects for significant reductions in CO2 emissions from the personal transport system.

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Appendices

A. Review of EPRI technical report 2001

This methodology review will have a focus on those parts of the EPRI (2001) which have been used in the present study.

The goal of the EPRI Technical Report was to compare vehicle efficiencies, emissions, cost, and customer preferences of hybrid vehicle options. Included options were: a conventional vehicle (CV), a hybrid vehicle without plug-in capabilities (HEV 0), and two plug-in hybrid vehicles (PHEV 20 and PHEV 60) with different electric-only ranges, 20 and 60 US miles, or 32 and 96 km, respectively (EPRI 2001, p. 2-1). It was decided by the EPRI Work Group (WG) that the vehicles should be closely comparable in performance. Thus the main components were specified and performance equivalence was achieved by changing the components specifications iteratively (EPRI 2001, p. 2-1).

The EPRI WG used the ADVISOR (ADvanced VehIcle SimulatOR), which is software for modeling vehicles components and characteristics. This model was developed by the US National Renewable Energy Laboratory with support of the US Department of Labor (EPRI 2001, p. 2-2).

The EPRI WG used an iterative process to design each HEV. The initial criteria were to meet or exceed the performance of the base CV in categories like: acceleration, top speed, gradeability, minimum towing capacity and minimum range targets. For the PHEV, these requirements were supposed to be met with down to nearly 20% state of charge (SOC). The EPRI WG also relaxed some HEV performance characteristics "…if matching a specific CV parameter would have increased the cost of the HEV design greatly with only a marginal useful gain for the vehicle owner/operator" (EPRI 2001, p. 2-2). After the process the WG ended with the results in Table A-1:

Table A-1 EPRI Vehicle options main characteristics (EPRI 2001).

Vehicle	CV	HEV 0	HEV 20	HEV 60
Engine Peak Power [kW]	127	67	61	38
Motor Rated Power[kW]	-	44	51	75
Battery Rated Capacity [kWh]	-	2.9	5.9	17.9
Battery Rated Power [kW]	-	49	54	99
Vehicle Mass [kg]	1682	1618	1664	1782
Power to Mass Ratio [W/kg]	77.65	68.81	67.48	63.25

The EPRI WG states that the hybridization of the drivetrain with electrical energy storage can reduce combustion fuel consumption in two ways. One way is that hybrid vehicles have smaller engines, which are operated in optimal efficiency conditions. The other way is that HEVs partly recover vehicle kinetic energy during braking or when going downhill (EPRI 2001, p. 2-4).

The EPRI WG uses as a first approach two efficiencies, the gasoline-only efficiency and the electric-only efficiency. All the vehicle options can have gasoline-only efficiency, which is the only efficiency for CV and HEV 0. The PHEVs have also the so called electric-only efficiency (EPRI 2001, p. 2-4).

PHEV can be operated only by electricity or as a hybrid vehicle with no plug-in capabilities. In the EPRI Technical Report, two concepts are used: the Mileage Weighted Probability (MWP) and the Utility Factor (UF). The MWP is an estimation of the part of the annual mileage that will be electric only. The UF is an electric-only operation factor defined by the Society of Automotive Engineers (EPRI 2001, p. 2-4) and it is based on additional weighting of the MWP.

The EPRI Technical Report included a survey among 386 people, and they also used the data of the US Department Transportation 1995 Nationwide Personal Transportation Survey. The EPRI WG defined the one way commute distance (to work) as the main variable that can be used for characterizing the driving pattern. The information obtained is summarized in the following table (EPRI 2001, p. 4-13).

Table A-2 Driving distances and patterns in the US (EPRI 2001).

One Way Commute Distance	< 5 mi (8 km)	5 to 15 mi (6 to 24 km)	> 15 mi (24 km)	Average
Annual Mileage	7 712 mi (12 339 km)	11 937 mi (19 090 km)	17 975 mi (28 760 km)	13 322 mi (21 315 km)
Lifetime years	10	8.4	5.6	7.5
Percent of households (vehicle)	27.5%	30%	42.5%	100%

It should be noted at this point that the EPRI WG has estimated MWP for the average, low, mid, and high commute distance for the HEV 20 and HEV 60 options. MWP are different dependent on the commute distance, and this is also related to the annual driving distance. The average driving distance in US is 13 322 US miles (21 315 km) and 27.5% of the households have an annual mileage of 7 712 US miles (12 339 km) (EPRI 2001, p. 4-14). In the EPRI Technical Report, the WG also comment that the charging frequency has a large effect in all-electric use (EPRI 2001, p. 3-14).

For presenting the results for efficiency of PHEVs, EPRI presents the equivalent fuel efficiencies in miles per US gallon (mpg) using the UF or the SAE J1711 factors. A value of 33.44 kWh per gallon has been used for conversion of electric only efficiency to gasoline equivalent. For PHEVs the EPRI Technical Report presents four fuel efficiencies, electric only, gasoline only, and two combined equivalents (EPRI 2001, p. 3-12).

The EPRI Technical Report estimates results about emissions also, like smog precursors (NOx and HC) and greenhouse gas (primarily CO2) (EPRI 2001, p. 3-33).

The EPRI Technical Report estimates the vehicle retail price equivalent and the operating costs. For the capital cost the EPRI WG used the vehicle Retail Price Equivalent (RPE), which is defined as the sum of all component costs, marked-up with dealer and manufacturer profits and overheads. The WG used two methodologies to estimate the vehicle retail price, the Base Method and the Argonne National Laboratory (ANL) Method (EPRI 2001, p. 4-2).

In the Base Method, component costs are estimated as the costs of labor and materials for component. Manufacturer and dealer mark-ups were applied to all components. Costs of development are also added (Electric Power Research Institute 2001, p. 4-2). In the ANL Method, the electric components like motor, controller and battery are assumed to be provided by outside vendors. Therefore some partial mark-ups are also added. A single mark-up covers manufacturer and dealer mark-ups and development costs (EPRI 2001, p. 4-2). According to the EPRI WG the Base and ANL Methods would be the lower and higher price cases (EPRI 2001, p. 4-1).

The WG set 2010 as the horizon for component and technology improvements. It is assumed that these improvements will occur reasonably. The costs are the expected for 2010 and at a level of production of 100000 units per year (EPRI 2001, p. 2-10). The costs of individual components are estimated using cost functions from some manufacturers.

In the EPRI Technical Report, it is assumed that batteries are the biggest cost; therefore a reduced mark-up is applied in both methods by the EPRI WG. It is stated that this approach was very controversial within the EPRI WG (EPRI 2001, p. 4-11).

The EPRI Technical Report also analyzed customer preference and commercialization issues. Customer preference was studied using focus groups, choice based market model, and direct assessment. Commercialization issues included technological barriers and opportunities, and policy instruments and incentives (Electric Power Research Institute 2001, p. 2-15).

Hybrid Vehicle Technology used in the EPRI Technical Report 2001

Basically the EPRI Technical Report begins with the definition of the vehicles to be included in the comparison, which are (EPRI 2001, p. 2-1):
- A conventional vehicle (CV) with an internal combustion engine (ICE). This vehicle is the base for comparisons of performance.
- A parallel hybrid with no plug-in capability (HEV 0), this vehicle has a small battery which is used for giving some power and for savings from regenerative braking.
- A parallel hybrid, which can be driven as an HEV 0, but has a bigger battery, which allows it to be driven only by electric traction, with an electric-only range of 20 US miles (32 km), this vehicle is defined as HEV 20.
- A parallel hybrid, which can be driven as an HEV 0, but has a bigger battery, which allows it to be driven only by electric traction, with an electric-only range of 60 US miles (96 km), this vehicle is defined as HEV 60.

It should be noticed that hybrid electric vehicles with plug-in capabilities are know as plug-in hybrid vehicles (PHEV). In the original EPRI Technical Report PHEV 20 was called HEV 20 and PHEV 60 was called HEV 60.

The EPRI WG did not include series hybrid configurations; because after initial estimations the EPRI WG realized that series hybrids tend to have smaller fuel economies than parallel hybrid vehicles. Also the WG initially had a HEV with 40 miles electric-only range; however it was realized that HEV 40 characteristics could be interpolated from HEV 20 and HEV 60 (EPRI 2001, p. 3-2).

The configuration of the vehicles includes the generic parallel HEV components. The drivetrain includes an ICE, a motor, and a continuous variable transmission (CVT) and some accessories. The energy storage includes battery and fuel tank. A charger is also needed (EPRI 2001, p. 3-24).

In the EPRI Technical Report the engine is a spark ignition engine (EPRI 2001, p. 4-3). The battery technology is NiMH (EPRI 2001, p. 4-8). The EPRI WG decided to use DC Brushless Permanent Magnet (BPM) motors because they can operate at any speed and are easier to control than AC induction motors (EPRI 2001, p. 4-4).

Another important aspect of HEV technology is the control strategy. In an HEV the vehicle's hybrid controller decides on how to operate the engine and the battery-motor combination (EPRI 2001, p. 3-16).

PHEV can operate in electric-only mode, using only the battery and motor for driving the vehicle. The PHEV modeled by EPRI were able to operate in electric-only mode up to 70 mph (112 km/h) (EPRI 2001, p. 3-16).

In the hybrid operation mode, there can be some variations like: working as a HEV 0, the engine is the main power source, but the motor-battery provide more torque when required. When the SOC is low, than a charge sustaining mode operation can be used to charge the battery again to the design SOC. When a PHEV is drived by the motor-battery and more torque is required, than the engine can provide some power as well. When the battery falls below 21% SOC and the entire electric-only range has been used, PHEV can work in motor assist. This operation is mainly done by the engine, but when more torque is required than the motor can provide some (EPRI 2001, p. 3-16).

The regeneration mode is done in the electric mode or the hybrid mode, and it uses the motor as a generator to charge the battery (regenerative braking). This mode takes place when the vehicle is going downhill or braking (EPRI 2001, p. 3-17).

The Low-Torque electric mode is a brief change from the Hybrid to the Electric mode, when the engine is working inefficiently for a longer than 4 seconds period, the engine is turned off and the motor provides the torque (EPRI 2001, p. 3-17).

The EPRI WG states that HEV 0, PHEV 20 and PHEV 60 use all operation modes during normal operation (EPRI 2001, p. 3-18).

Main conclusions of the EPRI Technical Report (EPRI 2001)

Here we select the most relevant conclusions of the EPRI Technical Report (EPRI 2001, p. 2-20)

- HEVs and PHEV can be designed to meet customers demand on performance and operation characteristics.
- Hybridization can offer significant efficiency improvements and reductions of emissions of air pollutants and CO2.

- Hybrid vehicle technology only requires evolutionary advantages to be technically feasible. NiMH are technically capable, but there are uncertainties regarding life and cost.
- Hybrid vehicles will cost more to produce than comparable CVs.
- Total energy and maintenance costs of PHEVs will be lower than those costs for CVs.
- There is market potential for hybrid vehicle, especially if they have the same cost as CVs.
- People are willing to pay more for hybrid options. People prefer to plug in a vehicle rather than to fuel it in a gas station.
- There is significant uncertainty regarding hybrid vehicles retail price.
- Incremental costs for all hybrid options are significant at low and medium level of production. The infrastructure issues for PHEVs are fewer compared to alternative fuel vehicles.

B. Component costs

Table B-1 presents the individual components cost obtained using function costs. Some components have fixed costs obtained from EPRI (2001).

Table B-1 Individual Component Costs (USD).

	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60	EV 60	EV 350	EV*
Engine	2077	1228	1156	1018	880	0	0	0
Engine Thermal Management	30	16	14	12	9	0	0	0
Exhaust	250	200	200	175	150	0	0	0
Engine Total	**2357**	**1444**	**1370**	**1205**	**1039**	**0**	**0**	**0**
Transmission	**1045**	**625**	**625**	**625**	**625**	**625**	**625**	**625**
Starter motor	40	0	0	0	0	0	0	0
Electric motor	0	797	893	1053	1213	1612	2763	1654
motor controller	0	478	528	611	694	899	1494	921
thermal management	0	114	121	133	145	174	258	177
Electric Traction Total	**40**	**1390**	**1542**	**1797**	**2052**	**2685**	**4515**	**2752**
Power Steering Pump	50	50	50	50	50	50	50	50
Generator/Alternator	40	0	0	0	0	0	0	0
A/C Compressor	100	100	100	100	100	100	100	100
A/C Condenser	20	20	20	20	20	20	20	20
APM	0	130	130	130	130	130	130	130
Accesory Power Total	**210**	**300**	**300**	**300**	**300**	**300**	**300**	**300**
Fuel Storage Tank	10	10	10	10	10	10	10	10
Accesory Battery	20	15	15	15	15	15	15	15
Battery Module	0	1311	2150	3977	5831	6377	30580	7215
Pack Hardware	0	478	497	534	572	572	1114	591
Pack Tray	0	148	167	204	242	242	784	261
Pack Thermal	0	101	112	134	157	157	482	168
Energy Storage Total	**30**	**2064**	**2951**	**4875**	**6827**	**7374**	**32985**	**8260**
Charger	0	0	380	380	380	380	380	380
Cable	0	0	150	150	150	150	150	150
Infrastrcture Upgrade	0	0	0	0	200	200	200	200
Charging Total	**0**	**0**	**530**	**530**	**730**	**730**	**730**	**730**
TOTAL Component Costs	**3682**	**5822**	**7318**	**9331**	**11573**	**11714**	**39156**	**12666**

C. Retail price of vehicle options

The following tables provide the retail prices of different vehicle options according to different specifications and different methods. The partial results at component groups level is also presented.

Table C-1 EPRI Specifications with EPRI Base Method (EPRI 2001 and calculated from EPRI 2001).

	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60	EV 60	EV 350	EV*
Engine Total	4112	2519	2391	2102	1812	0	0	0
Transmission	1823	1090	1090	1090	1090	1090	1090	1090
Electric Traction Total	70	2424	2690	3135	3579	4684	7877	4800
Accessory Power Total	366	523	523	523	523	523	523	523
Energy Storage Total	52	3768	4886	7209	9566	10202	41229	11275
Charging Total	0	0	925	925	1273	1273	1273	1273
Development Costs	90	440	460	460	460	460	461	462
Glider	12473	12473	12473	12473	12473	12473	12473	12473
Total (USD)	18990	23240	25440	27920	30780	30710	64930	31900
Total (SEK)	136710	167310	183150	201000	221600	221090	467470	229660
Incremental difference (SEK)		30600	46440	64290	84890	84380	330760	92950

Table C-2 EPRI Specifications with ANL EPRI Method (EPRI 2001 and calculated from EPRI 2001).

	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60	EV 60	EV 350	EV*
Engine Total	4715	2888	2741	2409	2078	0	0	0
Transmission	2090	1250	1250	1250	1250	1250	1250	1250
Electric Traction Total	60	2084	2313	2695	3077	4027	6773	4128
Accessory Power Total	420	600	600	600	600	600	600	600
Energy Storage Total	45	3240	4201	6199	8225	8772	35451	9695
Charging Total	0	0	795	795	1095	1095	1095	1095
Development Costs	0	0	0	0	0	0	0	0
Glider	11520	11520	11520	11520	11520	11520	11520	11520
Total (USD)	18850	21580	23420	25470	27850	27260	56690	28290
Total (SEK)	135720	155390	168620	183370	200490	196310	408160	203670
Incremental difference (SEK)	0	19670	32900	47650	64770	60590	272440	67950

Table C-3 EPRI Specifications with NREL Cost Method (EPRI 2001 and calculated from EPRI 2001).

	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60	EV 60	EV 350	EV*
Engine Total	4102	2512	2384	2096	1808	0	0	0
Transmission	1818	1088	1088	1088	1088	1088	1088	1088
Electric Traction Total	70	2418	2683	3126	3570	4672	7856	4788
Accessory Power Total	365	522	522	522	522	522	522	522
Energy Storage Total	52	3591	5134	8482	11879	12831	57395	14372
Charging Total	0	0	922	922	1270	1270	1270	1270
Development Costs	0	0	0	0	0	0	0	0
Glider	12400	12400	12400	12400	12400	12400	12400	12400
Total (USD)	18810	22530	25130	28640	32540	32780	80530	34440
Total (SEK)	135410	162220	180960	206180	234260	236030	579820	247970
Incremental difference (SEK)	0	26500	45240	70460	98540	100310	444100	112250

Table C-4 NREL Specifications and NREL Cost method (Simpson 2006, EPRI 2001 and calculated from Simpson 2006).

	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60
Engine Total	4005	2725	2810	2809	2787
Transmission	1818	1088	1088	1088	1088
Electric Traction Total	70	2103	2369	2444	2482
Accessory Power Total	365	522	522	522	522
Energy Storage Total	52	2762	6943	9806	11610
Charging Total	0	0	922	922	1270
Development Costs	0	0	0	0	0
Glider	17390	17390	17390	17390	17390
Total (USD)	23700	26590	32043	34982	37149
Total (SEK)	170642	191446	230712	251870	267476
Incremental difference (SEK)	0	20804	60070	81228	96834

D. Vehicle component mass

Table D-1 presents the masses for individual components taken from EPRI (2001). The mass of components of the additional vehicle options is calculated by obtaining mass functions based on EPRI (2001).

Table D-1 Components mass.

Component	CV	HEV 0	PHEV 20	PHEV 40	PHEV 60	EV 60	EV 350	EV*
Engine	156	87	79	65	50	0	0	0
Engine Thermal	8	5	4	3	3	0	0	0
Lube	8	7	5	5	4			
Engine Misc.	33	10	10	10	10			
Engine Mounts	5	5	5	5	5			
Engine Total	209	114	104	88	72	0	0	0
Exhaust/Evap System	41	32	30	26	22	0	0	0
Transmission	98	50	50	50	50	50	50	50
Generator/Alternator	5							
A/C Compressor	6	11	13	14	15	18	26	19
A/C Condenser	2	2	3	3	3	4	6	4
A/C Misc.	13	13	13	13	13	13	13	13
Accesory Power Module		10	10	10	10	10	10	10
Accesory Power Total	26	36	38	39	41	45	54	46
Starter Motor	6							
Electric Motor		24	27	33	40	53	89	57
Power Inverter		5	5	5	5	5	5	5
Motor/Electronics Thermal		17	17	17	17	17	17	17
Electric Traction Total	6	45	49	55	62	75	111	78
Fuel Storage (tank + lines)	13	9	8	8	8			
Accesory Battery	15	5	5	5	5	5	5	5
Energy Batteries		94	151	217	315	305	1552	348
Pack Tray		7	10	19	22	26	135	30
Pack Hardware		14	14	14	14	14	14	14
Battery Thermal		15	15	15	15	15	15	15
Energy Storage Total	28	143	202	277	378	364	1719	411
Charge Port			7	7	7	7	7	7
Charging Total	0	0	7	7	7	7	7	7
TOTAL POWER TRAIN	408	420	480	543	631	541	1942	592
Glider (including power steering)	1053	1053	1053	1053	1053	1053	1053	1053
Mass of fuel for full tank	38	28	26	25	25			
TOTAL CURB MASS	1500	1500	1559	1622	1709	1594	2995	1645
Driver and cargo mass	136	136	136	136	136	136	136	136
TOTAL TEST MASS	**1636**	**1636**	**1695**	**1758**	**1845**	**1730**	**3131**	**1781**

Data from EPRI 2001

E. Swedish driving patterns

Table E-1 presents the total driving distance by car per day. This has been used for the calculation of the EDF. Data is provided by SIKA.

Table E-1 Swedish driving patterns.

Total reslängd med bil per dag / **total trip distance BY car PER day**										
	- <2 km	2- <5 km	5- <10 km	10- <20 km	20-<50 km	50-<100 km	100 km -	Totalt		
	2	5	10	20	50	100	200			
	Antal	Antal	Antal	Antal	Antal	Antal	Antal	Antal	%	cummulative %
Km PER car and day										
Km per bil och										
dag										
- <2 km	39142	1943	1499	.	478	.	300	43362	1%	1%
2- <5 km	.	274524	3937	3396	3880	531	1049	287317	6%	7%
5- <10 km	.	.	446719	9426	4960	4693	5376	471173	10%	17%
10-<20 km	.	.	.	809407	15881	3712	837	829837	17%	34%
20-<50 km	.	.	.	.	1538023	19720	3254	1560997	33%	67%
50-<100 km	.	.	.	.	.	993742	4023	997765	21%	87%
100 km -	.	.	.	.	.	.	607929	607929	13%	100%
Totalt	39142	276467	452154	822229	1563222	1022399	622768	4798380		
%	1%	6%	9%	17%	33%	21%	13%			
cummulative %	1%	7%	16%	33%	66%	87%	100%			

Data personal communication with SIKA

F. Potential off-peak capacity and CO2 emissions from electricity

In this appendix the potential off-peak capacity is calculated. Data for calculation of CO2 emissions from average electricity in Sweden is presented also.

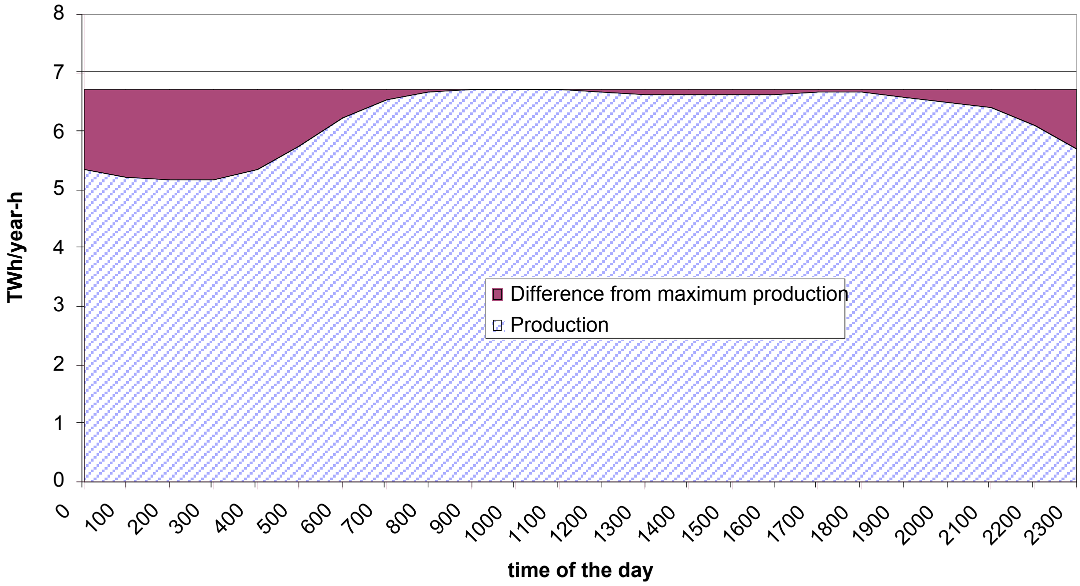

Figure F-1 Swedish total production of electricity and calculated potential off-peak capacity in low-load hours in year 2005 (adapted from data provided by SVK 2006, pers. comm. 4 October and 28 September).

Table F-1 Production of electricity and off-peak capacity in TWh in Sweden 2005.

Total production	149.7
Total Off-peak capacity [a]	12.1
Off-peak capacity (22h00 to 6h00) [b]	10.1

[a, b] Assuming that there is always enough water in the reservoirs of hydro power plants.

Table F-2 Consumption of fossil fuels in electricity production in Sweden 2005 and their CO2 emission factors.

Type of fossil power	Emission factor [a] [kg CO2/kWh]	Production [b] [TJ]
hard coal	0.335	3211
Turf	0.386	2429
kerosene	0.216	18
diesel oil	0.261	0
domestic fuel oil	0.267	625
fuel oil, light	0.274	569
fuel oil heavy	0.274	5808
natural gas	0.203	2285
Coke oven gas	0.167	717
Blast furnace gas incl. LD-gas	1.076	8547
LPG		0
Solid waste	0.216	2334

[a] Statistics Sweden n.d.

[b] Swedish Energy Agency and Statistics Sweden, 2006

G. PHEV charging

Table G-1 shows information from EPRI adapted for Swedish conditions of standard outlet configuration. The first row shows the typical Swedish circuit characteristics. The second row shows the charging times using a typical Swedish outlet for stoves. This situation probably implies an infrastructure upgrade. In the last case the charging times are considerably shorter than in the typical outlet case.

It should be noticed that the times in the table are for charging the battery from empty; therefore this is an extreme worst case. In the case of PHEV 60, it is not likely that it will be totally discharged every day. The charging of a PHEV 20 would not require an infrastructure upgrade, because the charging time is less than 6 hours, which seems reasonable considering nightly charging.

Table G-1 Charging time for different PHEVs (Adapted from EPRI (2001)).

Circuit		Charger size	Charging Rate	Charging Time [hr]			Infrastructure Upgrade
Volts	Amp	kW	kWh/hr	PHEV 20	PHEV 40	PHEV 60	
220	10	1.9	1.3	5.7	11.4	17.3	Not Required
380	25	7.7	5.7	1.3	2.6	3.9	Required

One important practical issue is the requirement of access to an outlet, at least over night for the cars. Three categories can be identified:

- Car owners who leave the car on the streets over night
- Car owners who park the car in parking buildings over night; and
- Car owners who have a garage in their houses and leave them there over night

The first group has practical obstacles for having a PHEV. The introduction of PHEVs in the Swedish fleets may offer new possibilities like charging parking slots, which might attract car owners of this group. Another solution would be the installation of outlets in the streets close to the cars.

The second group seems to have reasonably good practical conditions for charging a PHEV over night, because the upgrade would have to be made to a building with a lot of parking slots. Therefore they would benefit from high volume prices. In these cases increasing the amperage of the circuits may be considered.

The third group apparently would only need to get an extension cable, if an outlet is not close enough to the car. Thus this group would be ready to get a PHEV.