EVS 25

Sustainable Mobility Revolution

November 5-9, 2010 Shenzhen, China

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The EVS series began in 1969 as an academic forum for global networking and the exchange of technical information. As electric drive technologies progressed from the classrooms and laboratories into the marketplace, EVS blossomed into an event both academic and business oriented.

Today, the EVS series is recognized as the global electric transportation industry's premier and largest forum, showcasing all forms of technologies in the market place and on the drawing boards--from low speed battery electric vehicles to fuel cell electric buses. The event attracts academic, government and industry leaders from around the world who are interested in exploring and understanding the technical, policy and market challenges to a paradigm shift toward use of electric transportation technologies.

And EVS25 will be held Nov 5-9 at the Shenzhen Convention & Exhibition Center, China.

Oral Session

08:00-10:00 Monday, November 8, 2010
Session 1A: Vehicles & Transportation Systems
Room: Chrysanthemum Hall(菊花厅)

Chairpersons: CHENG Jung-Ho, National Taiwan University;
Ed Benjamin, eCycleElectric Consultants

◆ Richard Barney Carlson, Idaho National Laboratory, United States
Primary Factors that Impact the Fuel Consumption of Plug-In Hybrid Electric Vehicles

◆ Maximilian Kloess, Viennar University of Technology, Austria
The role of plug-in-hybrids as bridging technology towards pure electric cars: An economic assessment

◆ Chang Woo Shin, Seoul National University, Korea
A Study on Quantitative Evaluation of Drivability in HEVs

◆ Michael Duoba, Argonne National Laboratory, United States
Development and Investigation of Practical (Shortened) Standard Test Procedures for BEVs

◆ WANG Zizi, National University of Singapore, Singapore
Experimental Study of Electric Vehicle Performance in Singapore

◆ Yun-Jie Hsu, National Taiwan University, Taiwan, China
Effect of Vehicle Control Unit Parameters on Electric Vehicle Driving Operation Responses

◆ Christos Loakimidis, MITPortugal, MITEnergy Initiative, Greece
Pathways towards an Electric Vehicles Society

◆ Adriano Alessandrini, CTL - Sapienza University of Rome, Italy
Evaluation of a multipurpose hybrid vehicle concept

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The role of plug-in-hybrids as bridging technology towards pure electric cars: An economic assessment

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Abstract— The paper gives an economic assessment of Plug-In Hybrid cars. It analyses the impact of fuel prices and battery cost on their economic competitiveness and on the optimal electric driving range. To determine the proportion of electric driven kilometers to the overall kilometrage of the PHEV, data on average driving behavior of passenger car drivers in Austria is used.

In a first step the total cost of ownership of different vehicle technologies are analyzed including conventional cars, hybrids, electric cars and different two types of PHEVs. To assess the impact of battery costs, the capital cost analysis is performed on a component basis. Furthermore the role of different layouts of PHEVs in terms of electric driving range (respectively battery size) is analyzed from an economic perspective.

The results point out the key role PHEVs can play as a bridging technology toward pure electric driving. They can act as a driver of battery technology by raising production scale and thereby help reducing cost. This leads to higher optimal electric ranges causing every PHEV generation to have longer electric driving range and thereby would assure an increasing percentage of trips and kilometers driven on electricity. *Copyright Form of EVS25***.**

Keywords— Plug-In Hybrids, cost assessment, electric driving range

1 Introduction

Low efficiency, fossil fuel dependence and emissions are some of the crucial problem the passenger cars are facing today. The electric car is a promising solution that could solve some of these problems. It has significantly higher efficiency than conventional, internal combustion engine ICE based cars and has no direct exhaust gas emission, which makes it environmentally more benign. Furthermore, electricity can be produced from various fossil and renewable sources leading to a better diversification of energy sources.

In the past years and decades there have been various attempts to bring electric cars on the market. Their economic success however, has always been very modest and they have never made it to the mass market. The main obstacles have been their high price and their insufficient driving performance, especially in terms of driving range. Both problems are rooted in the electricity storage systems that appear to be unable to meet the performance requirements of passenger cars.

Plug-In Hybrids could offer a solution to this problem as they combine the main strengths of conventional and electric propulsion technologies. Being able to drive most trips in electric mode with high efficiency and low emissions they have all the advantages of all electric cars. With the ability to switch in the ICE mode they also have high driving range and fast refueling ability which makes them a full-value car. Therefore PHEVs would address the entire car market and not only niches like pure battery electric vehicles do.

In this paper an economic assessment of PHEVs is performed to find out under which framework conditions PHEVs can be competitive to cars with conventional drive CD and hybrid electric vehicles HEV. Furthermore, the role of the electric range respectively the size of the battery of the PHEV is analyzed.

2 Methodology

In a first step the powertrain systems have been modeled based on their main component groups to estimate the fuel consumption and cost of the vehicles.

Secondly an assessment of total cost of all propulsion systems has been performed to identify the framework conditions (fuel price & technology cost) necessary for PHEVs to become economically competitive.

Thirdly the optimal driving range of PHEVs from an economic perspective has been analyses by considering the inter-relation between electric driving range and percentage of driving distance travelled in electric mode.

2.1 Vehicle cost model

For this purpose a vehicle cost model has been made that contains detailed bottom up data on all powertrain systems. To analyze the impact of the costs of key components (above all batteries) the vehicles were modeled on a component basis. To make the powertrain systems comparable a reference vehicle was defined with characteristics that correspond to an average European middle class car. The vehicle mass was set at 1500kg and the engine power at 75kW.

The analyzed drivetrain configurations are a PHEV with a parallel, power split hybrid system comparable to the one used in the Toyota Prius (see Figure 1). The pure electric driving range was set at 40km, while the overall range would be up to 700km. The other PHEV is a series hybrid car with the same electric driving range of around 40km and a 40kW gasoline ICE serving as range extender permitting an overall driving range of up to 700km.

Those two PHEVs are compared with a conventional drive gasoline powertrain system, a mild hybrid system, a full hybrid power-split systems and a pure electric car with 180km electric driving range (see Table 1)

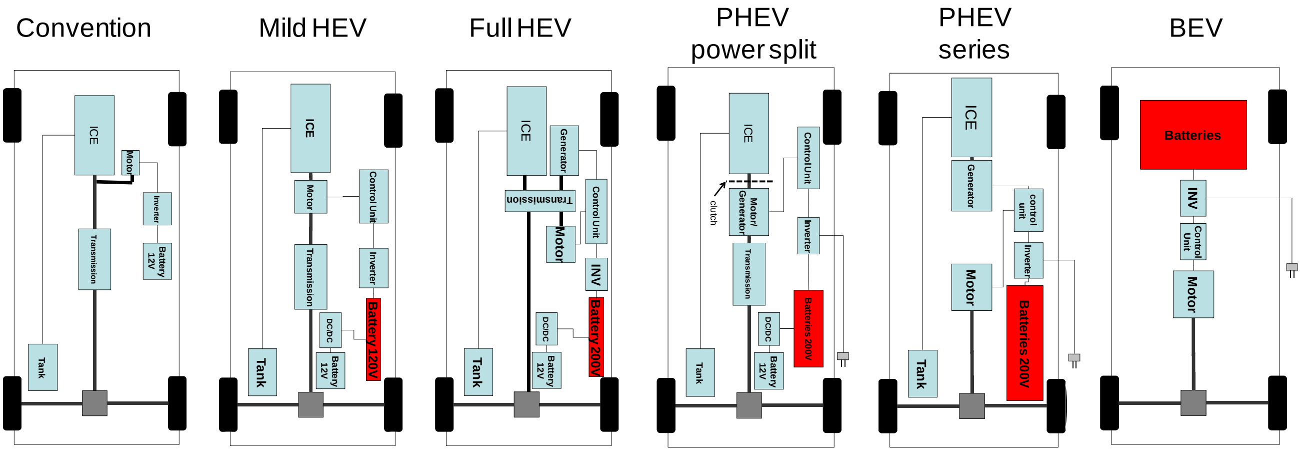

Figure 1: Powertrain configurations

Table 1: Characteristics of cars with differen powertrain systems

	electric range	overall range	power engine	 e-motor	curb weigth	battery capacity	battery mass	fuel consumption
	[km]	[km]	[kW]	[kW]	[kg]	[kWh]	[kg]	[l;kg;kWh 100km-1]
Conventional Drive - Gasoline		700	75		1,470			7.5
Mild Hybrid - Gasoline		700	65	20	1,460			6.4
Full Hybrid - Gasoline		700	50	50	1,488			5.9
Plug-In-Hybrid - Gasoline	40	700	50	50	1,538	10	100	5.9
Series Hybrid - Gasoline	80	700	40	75	1,623	20	200	5.5
Electric Vehicle	200	200		75	1,678	50	500	22.2

2.2 Purchase cost

To assess the purchase costs for the different powertrain systems for the status 2010 a detailed component based analysis was performed for all powertrain systems.
The cars are split up in the following component groups:

- **Vehicle basis:** It has been assumed that all vehicles share the same vehicle basis. It contains all components of the vehicle that are not relevant for the propulsion. This includes the vehicle chassis, the undercarriage (including the steering), the interior equipment including all comfort and security features, the exterior equipment (e.g. tyres, mirrors, windows etc.), the entire on board electricity grid (12V) and all the equipment for the control of vehicle functions. The corresponding costs were estimated based on Austrian passenger market data [1] [2].
- **Internal combustion engine:** The component group internal combustion engine includes apart from the engine itself, the transmission and the driveshaft. The costs of the internal combustion engine were set according to [3].
- **Electric drive system:** The electric drive system includes electric machines, the motor control unit, current converters and the electric charger if applicable. The cost of the electric machines and controllers were set according to [3] and the cost of the charger was set according to [4]
- **Battery system:** This component group includes starter and traction batteries. As starter battery ordinary lead acid technology has been assumed while the traction batteries have been assumed to be Lithium Ion based cells. Furthermore the component group includes the battery control units and the thermal control system.
There is currently some uncertainty on the actual system cost of lithium ion battery systems. As showed in Table 2 there is discrepancy within the estimations that can be found in this field. According to the data found in literature the specific system cost lie between 500 and 1000€ kWh^{-1} depending on the assumed production volume. In this analysis the cost of Li-ion battery

system with an energy density of 100Wh kg^{-1} has been assumed to be 700€ kWh^{-1}.

Table 2: Energy density and cost of lithium ion batteries [5] [6] [7]

Source	Energy Density [Wh kg-1]	Cost [€ kWh-1]	
Matheys et al 2005	125	700-860	
Conte et al. 2004	125	300	(@100k units/a)
Passier et al. 2007	110-220	150-600	
Vliet et all 2010	90-110	1000-1600	

- **Tank System:** In this analysis the tank system only includes an ordinary gasoline tank whose cost has been determined according to [3].

Table 3: net purchase costs and component costs of analyzed propulsion systems

		conventional drive (CD)	mild hybrid	full hybrid (power split)	PHEV 40 (power split)	PHEV 80 (series hybrid)	BEV 180	Source:
vehicle basis	[€]	14,223	14,223	14,223	14,223	14,223	14,223	market based estimations
Internal combustion engine (ICE)	[€]	3,454	3,162	2,723	2,723	2,430		EUCAR-CONCAWE-JRC-2007
electric drive components								
electric motors+controllers	[€]		540	1,904	1,904	3,119	2,039	EUCAR-CONCAWE-JRC-2007
drivetrain adaption	[€]		1,015	2,330	2,330			EUCAR-CONCAWE-JRC-2007
on-board charging system	[€]				500	500	500	Williams & Kurani 2007
battery system	[€]	100	800	1,500	7,000	14,000	35,000	
fuel tank	[€]	125	125	125	125	125		EUCAR-CONCAWE-JRC-2007
Total cost	[€]	17,902	19,865	22,805	28,805	34,397	51,762	

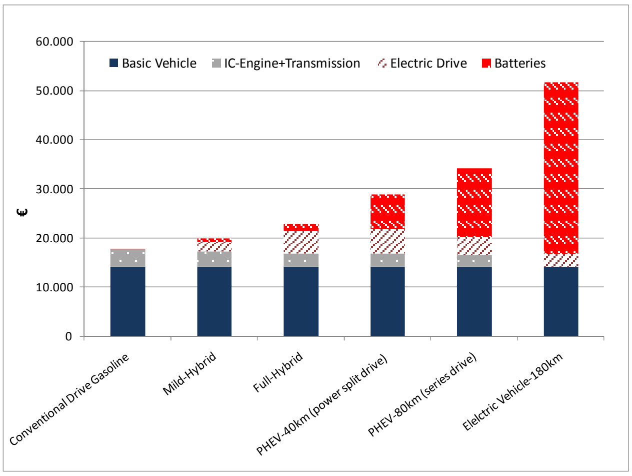

Figure 2: Net capital cost of different powertrain systems

2.3 Fuel consumption

For all analyzed propulsion systems the fuel consumption has been determined. For a better understanding of the key factors affecting fuel consumption the physical background of fuel consumption will be briefly summarized:
According to [7] and [8] the energy a car requires for driving can be defined as follows:

$$P_{total} = \frac{P_W}{\eta_{drivetrain}} + P_{aux} \qquad (1)$$

$$P_W = F_W \cdot v \qquad (2)$$

$$F_W = F_{RO} + F_L + F_{ST} + F_B \qquad (3)$$

Where P_w is the power needed to overcome the driving resistances F_w, $\eta_{drivetrain}$ is the efficiency of the drivetrain including motor and transmission and P_{aux} is the power required for the auxiliaries. The driving resistance F_w is determined by the rolling resistance F_{RO}, the aerodynamic drag F_L, the climbing resistance F_{ST} and the acceleration resistance F_B.

$$F_{RO} = f \cdot m \cdot g \qquad (4)$$

$$F_L = c_W \cdot A \cdot \rho \cdot \frac{v^2}{2} \qquad (5)$$

$$F_{St} = m \cdot g \cdot \sin\beta \qquad (6)$$

$$F_B = m_{red} \cdot dv / dt \qquad (7)$$

F_W………total driving resistance
F_{RO}……..rolling resistance
F_L………aerodynamic drag
F_{ST}………climbing resistance
F_B………acceleration resistance
f…………rolling resistance coefficient

m……….*vehicle mass*
g………..*gravitational acceleration*
c_W………*aerodynamic drag coefficient*
ρ………..*air density*
v…………*vehicle speed / speed of air flow*
β………..*angle of elevation*
m_{red}…….*dynamic mass considering mass moments of inertia of rotating elements*

The rolling resistance F_{RO} of the tyres depends on the vehicle mass, the quality of tyres and the state of the road. Secondly there is the aerodynamic drag F_L.
Thirdly there is the acceleration resistance that is highly dependent on the vehicle mass. The acceleration resistance is especially important in urban driving cycles due to the frequency of stop-and-go driving. Another driving resistance is the climbing resistance F_{ST}.
The equations show that vehicle mass strong impact on fuel consumption, which is important fact especially for electric cars where increasing electric range leads to an increase in vehicle mass (see section 2.4).
The efficiencies of the different propulsion systems used in this analysis have been determined by Researchers of AVL List, a company specialized on automotive Research and Development. The efficiencies of the technical status 2010 have been determined with vehicle simulation tools developed by AVL. The results are tank to wheel (TTW) efficiencies of all vehicles and powertrain systems and their corresponding fuel consumptions for a combined test cycle (ARTEMIS and NEDC) [9] (see table Table 1).

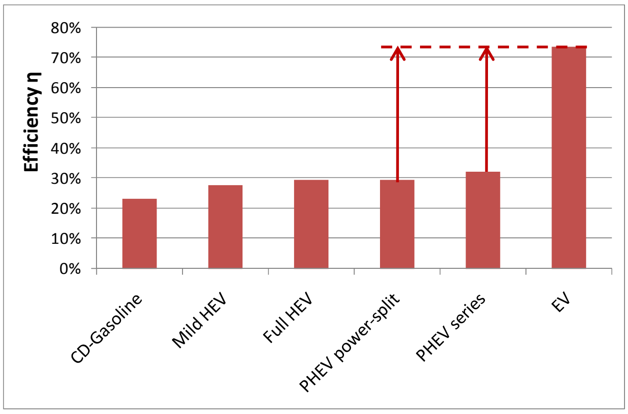

Figure 3: tank-to-wheel (TTW) efficiency of propulsion systems

2.4 Driving range

The lack of driving range has always been one of the main barriers of electric propulsion systems. Even though electricity storage systems improved considerably in the last years, they still cannot meet consumer expectations concerning driving range since they are strongly affected by the range of conventional cars. Because of high energy density and the good onboard storability of liquid gasoline and diesel conventional cars are able to run 500-1000km without refueling.
Figure 4 and Figure 5 demonstrate that even with the current technology status electric cars cannot achieve comparable driving ranges of conventional cars due to technical constraints. They show the effect of the necessary additional energy storage system on the overall curb weight of the cars. In the case of conventional cars the mass of the additional gasoline that has to be stored on board is almost negligible while in the case of an electric car a driving range of 500km would lead to a doubling of the vehicle mass.
Also from an economic perspective long driving ranges are not feasible due to the high cost battery systems which are still a major cost driver in electrified propulsion systems (see section 3.1).

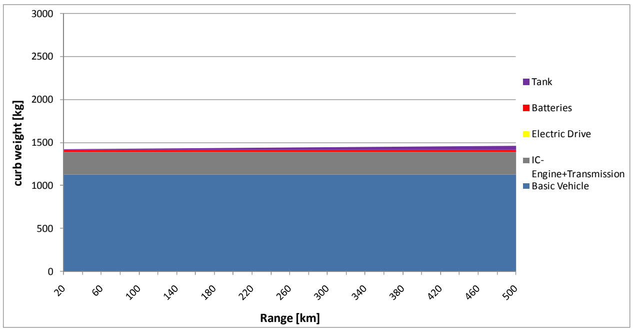

Figure 4: Effect of driving range on the curb weight of conventional cars

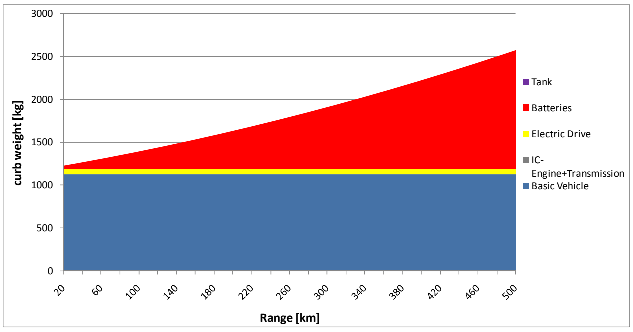

Figure 5: Effect of driving range on the curb weight of electric cars

PHEVs could be a possible option to compensate the range deficits of electric cars. Figure 6 shows the effect of increasing driving range on the vehicle mass on the example of an 80km-range PHEV with series hybrid drive. By only offering a short electric driving range the vehicle mass can be kept within an acceptable rang (+150kg) while the car also offers an overall range of >500km.

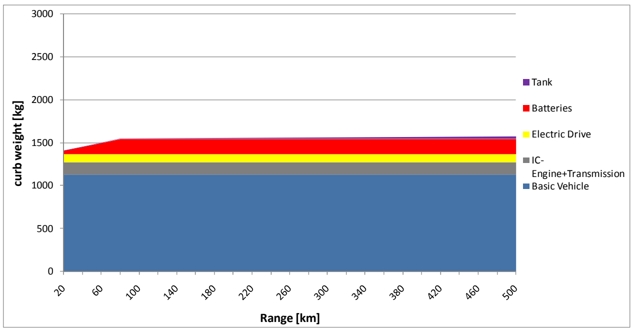

Figure 6: Effect of driving range on the curb weight of PHEVs (80km electric reange, series hybrid)

Even at the lower electric ranges of PHEVs the battery system is still a major driver of curb weight and vehicle cost. Therefore the dimensioning of the optimal electric driving range is a critical issue.

To find out the optimal driving range of a PHEV for the case of Austria the country specific user pattern of passenger cars has been used. Figure 7 shows the frequency and length of passenger car trips in Austria [10]. It shows that more than 90% of the trips conducted with passenger cars are below 50km and about 80% of the kilometers are travelled in trips shorter than 100km.

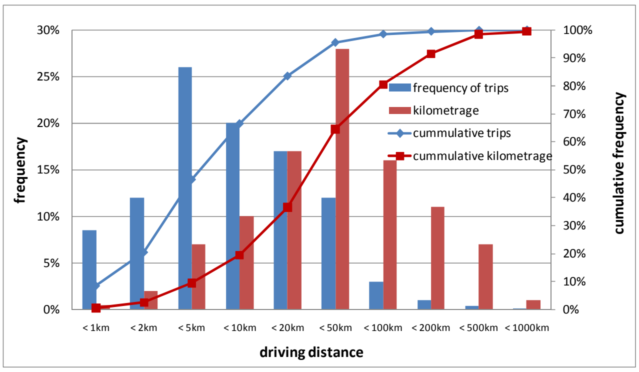

Figure 7: Average user profile of passenger cars in Austria (Data Source: VCÖ 2009)

From this empiric data the inter-relation between electric driving range R_{elect} of the car and percentage of yearly kilometers d_{elect} that are driven in electric mode have been derived. Thereby the cumulative frequency was approximated by a weibull distribution function *f*:

$$d_{electr} = f(R_{elect}) \ [\%] \qquad (8)$$

2.5 Total cost

In the costs assessment of the propulsion technologies *j* the capital costs *CC* and energy costs *EC* have been considered and total cost *SC* has been calculated on a yearly basis. The lifespan *DT* (depreciation time) of the cars has been assumed to be 10 years and the yearly driving distance *D* has been set at 20 000km.

$$SC_j = EC_j + CC_j \quad [€\ \text{year}^{-1}] \qquad (9)$$

Total cost of ownership would actually also include other types of cost such as maintenance, insurance etc. These costs have not been considered in the assessment since there are no indications that they might be differ strongly depending on the propulsion technologies.

Taxes have only been considered for fuel but not for cars. In the European Union there are very different schemes of passenger car taxation. The existing schemes of tax on acquisition and tax on ownership are extending from no taxes at all up to very high rates in single countries [11]. Considering vehicle taxes could lead to a strong distortion in an economic assessment. Actually also fuel taxes are different thought the EU. However, the variation is much smaller and they are all affected by one global factor which is the crude oil price.

The annual energy cost is determined by the fuel consumption *FC* of the car, the price *FP* of the fuel *i*, and the yearly driving distance *D*.

$$EC_j = FC_j \cdot FP_i \cdot D \quad [€\ \text{year}^{-1}] \qquad (10)$$

In the case of a PHEV two types of energy consumptions have to be considered: energy consumption in electric mode EC_{PHEV_electr} and energy consumption in gasoline mode $EC_{PHEV\_gasoline}$.

$$\begin{aligned} EC_{PHEV} &= EC_{PHEV\_gasoline} + EC_{PHEV\_electr} = \\ &= D \cdot (FC_{PHEV\_gasoline} \cdot FP_{gasoline} \cdot (1 - d_{electr}) \ [€\ \text{year}^{-1}] \\ &+ FC_{PHEV\_electr} \cdot FP_{electr} \cdot d_{electr}) \end{aligned}$$
(11)

Net capital costs CC of propulsion technologies j are the calculated based on the cost of their main components CC_{comp}:

$$\begin{aligned} CC_{SP\_j} &= \alpha \cdot \sum CC_{comp\_j} \quad [€\ \text{year}^{-1}] \qquad (12) \\ &= \alpha \cdot (CC_{basis\_j} + CC_{e-drive\_j} + CC_{Tank\_j} + CC_{battery\_j}) \end{aligned}$$

$$\alpha = \frac{(r * (1+r)^{DT}}{(1+r)^{DT} - 1} \qquad (13)$$

α … annuity factor
r … interest rate (r=5%)

The cost of the battery systems $CC_{battery}$ is a function of the electric range R_{elect}, the fuel consumption in electric mode FC_{elect_j} and its specific cost C_{sp_bat}.

$$CC_{battery\_j} = f(R_{elect}; FC_{elect\_j}; C_{sp\_bat}) \quad [€\ \text{year}^{-1}] \ (14)$$

3 Results

3.1 Total cost assessment

In the cost assessment the necessary framework conditions for PHEVs to become economically competitive to conventional and hybrid powertrain systems. have been determined. The results show the fuel prices and battery costs that are necessary for PHEV-40 to become the least cost propulsion technology. At the current battery system costs (status 2010), which have been estimated to be 700 € kWh^{-1}, the gasoline price has to be at least 2€ for a PHEV-40 to become cost effective (see Figure 8). On the other hand at a gasoline price of 1.5€ l^{-1}, battery systems cost have to be below 400€ kWh^{-1} for a PHEV to be economically competitive (see Figure 9). The electricity price has been set at 0,20€ kWh^{-1} in the entire analysis. The resulting framework conditions in terms of fuel prices and battery costs where the PHEV 40 with series hybrid drive becomes economically competitive are illustrated in Figure 10.

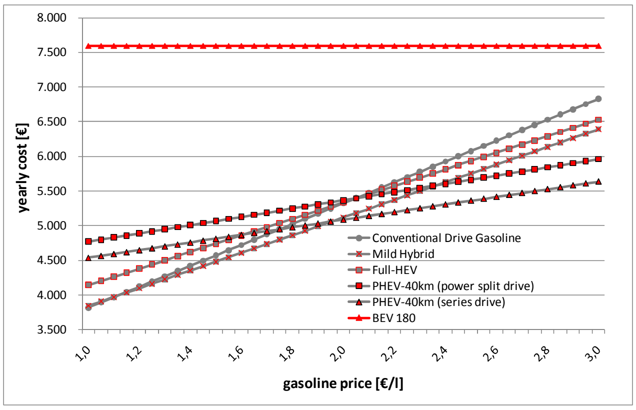

Figure 8: Sensitivity of yearly cost with respect to yearly gasoline price

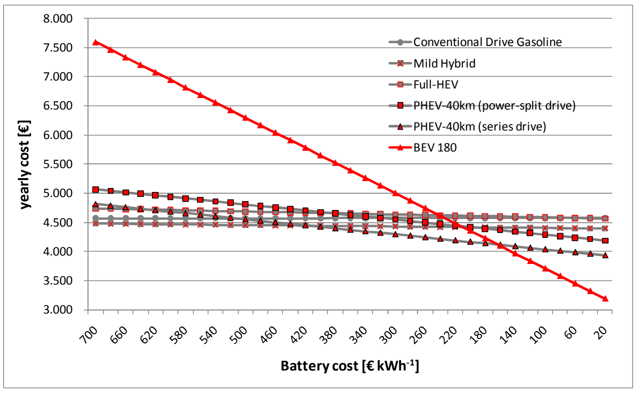

Figure 9: Sensitivity of yearly cost with respect to specific battery cost

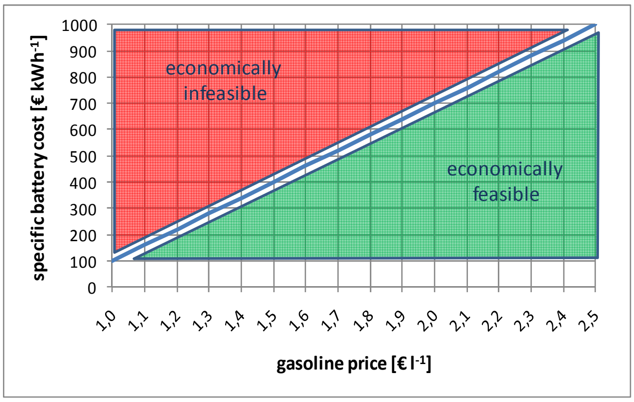

Figure 10: necessary framework conditions for a PHEV-40km to become economically competitive

3.2 Optimal electric driving range

Figure 11 illustrates how the optimal electric driving range has been determined for the PHEV (series drive). The total costs per year consist of capital cost, gasoline cost and electricity cost. With increasing electric range capital cost increase, due to the higher cost of the required battery system. Also the share of electricity cost within total cost increase with higher electric ranges due to the fact that a higher percentage of trips respectively kilometers can be travelled in electric mode (cf. section 2.4). The figure indicates that there is an optimal electric driving range for the PHEV at the respective framework conditions (battery cost: 350€ kWh^{-1}; gasoline price: 2€ l^{-1})

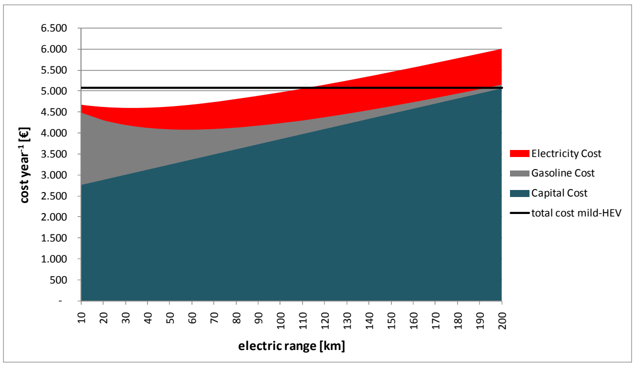

Figure 11: yearly cost of a PHEVs plotted against its electric driving range (battery cost: 350€ kWh^{-1}; gasoline price: 2 € l^{-1})

Figure 12 illustrates how the gasoline price affects the optimal electric driving range. With increasing gasoline prices the optimal driving range increases. Also a decrease in battery cost leads to an increasing optimal electric driving range (see Figure 13).

Table 4 gives the optimal driving ranges resulting from combinations of battery costs and gasoline prices.

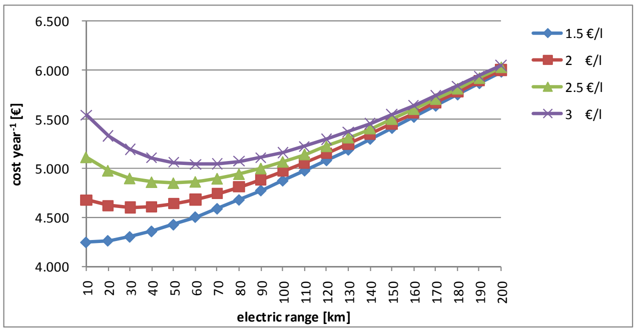

Figure 12: total cost per year of the PHEV at different fuel prices plotted against its electric driving range (battery cost: 350€ kWh^{-1})

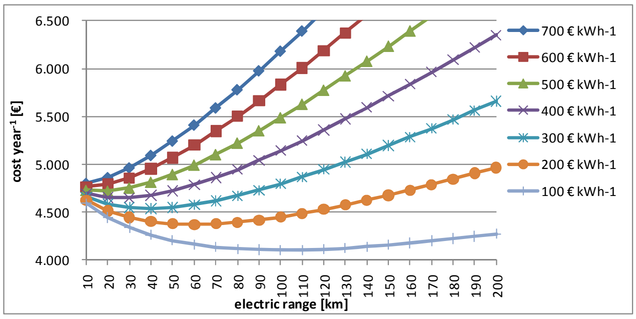

Figure 13: total cost per year of the PHEV at different battery costs plotted against its electric driving range (gasoline price: 2 € l^{-1})

Table 4: optimal electric driving ranges of PHEVs depending on gasoline price and battery cost

			gasoline price [€/l]			
			1.5	2	2.5	3
battery cost [€ kWh-1]	700		<10 km	10 km	20 km	30 km
	500		10 km	20 km	30 km	40 km
	300		20 km	40 km	60 km	70 km
	200		30 km	60 km	80 km	100 km
	100		70 km	100 km	120 km	140 km

4 Conclusion

The results indicate that PHEVs require either higher fuel prices or lower battery costs to be able to compete with conventional and hybrid technologies. However, increasing fossil fuel prices and reductions in battery costs could make them cost effective within the next years.

The results also point out the key role PHEVs can play as a bridging technology on the way toward pure electric mobility. Increasing fuel prices together with decreasing battery system costs lead to higher optimal electric driving ranges and consequently higher numbers of trips and distances travelled in electric mode.

In the coming years framework conditions are likely to develop in favor of PHEVs and could make them cost effective. From an economic perspective the first generations would still have relatively low electric driving ranges, but electric range would increase with every generation, driven by the battery cost reduction caused by increasing production scales and by the expected increase in fossil fuel prices. This development could lead to a point where PHEVs with sufficient driving range to drive 80-90% of yearly kilometers in electric mode would become cost effective.

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