The Consumption of Electrical Energy of Plug-in Hybrid Electric Vehicles in Belgium

Clement-Nyns Kristien, Van Reusel Koen, Driesen Johan

Katholieke Universiteit Leuven, Department of Electrical Engineering -Electa, Kasteepark Arenberg 10, B-3001Heverlee – Kristien.Clement@ESAT.Kuleuven.be

EET-2007 European Ele-Drive Conference
Brussels, Belgium, May 30 – June 01, 2007

Abstract

Alternative vehicles based on internal combustion engines (ICE), for instance the hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and the fuel cell electric vehicle FCEV, become more and more popular. HEV are at the moment commercial available and PHEVs will be the next phase in the evolution of hybrid and electric vehicles. One of the goals of this paper is to investigate the amount of electrical energy the distribution grid has to deliver for recharging the batteries of a PHEV fleet for the period 2003-2050 for Belgium. The vehicle-kilometres and the number of passenger cars are calculated with the TREMOVE model [1]. For 2030, this electrical energy is at maximum 5.1% of the generated electricity in Belgium, assuming that all HEVs are PHEVs and depending on the scenarios of the PRIMES model [2]. This gives an indication of the potential for PHEV. The better fuel efficiency of the HEVs and PHEVs reduce emissions up to about 1 Megaton per year for Belgium depending on the scenarios [2]. For the calculation of the fuel cost for PHEVs, the price of electricity has to taken into account. The price of electricity is very uncertain for the future.

Keywords: Plug-in hybrid electric vehicle, energy consumption, emissions, fuel cost.

1 Introduction

Because of the large dependency of Belgium on imported fossil fuels, it is useful to find alternatives, like (HEVs), to decrease this dependency. Other main drives for the development of HEVs are the increased energy efficiency, the acoustic noise reduction and the growing concern of the role of greenhouse gases such as CO_2 in the global warming and Kyoto restrictions. The downsizing of the internal combustion engine (ICE) is possible without losing performances because of the electric motor that has a potential for a power boost. The HEV always operates near optimum and consumes therefore less energy for the same performances.
HEVs combine two or more different energy sources. The most common combination is an ICE (gasoline or diesel) and an electric motor. There are several engine architectures possible, such as parallel and series hybrids. The wheels are driven by an electric motor in series hybrids. The energy for this motor is derived from the batteries or from the ICE. The ICE takes care of the average power and the batteries are stored with the excess of energy and provide energy when needed. For parallel hybrids, both the ICE and the electric motor drive the wheels. The ICE works jointly with the electric motor to deliver movement to the vehicle. The size of the ICE and the electric motor differs depending on the electric driving possibilities (light, mild and full). Light HEVs have an ICE with a starter generator which is designed to shut off the ICE during stops to save fuel. Mild HEVs have an electric motor of 10-20 kW which permits the start/stop function and provides also a power boost to the ICE. Full HEVs are capable to drive in electric-only mode for a limited range.

Batteries are used for energy storage but unfortunately, with the current technology, the electric drive range is rather limited. Another option for energy storage is a supercapacitor of which the power/energy ratio is much higher compared to batteries. Also the performance is more linear and does not decrease at low temperatures. So supercapacitors are a serious alternative to batteries for use in hybrid electric vehicles [3]. Flywheel energy storage works by accelerating a rotor to a very high speed and maintaining the energy in the system as inertial energy. The flywheels play a role in some futuristic engine designs and in the conjunction with other energy storage devices. Unlike batteries, flywheels are not affected by temperature changes and do not suffer from memory effect. The major problem is the gyroscopic effect.

Plug-in hybrid electric vehicles (PHEV) are the next phase in the evolution of hybrid and electric vehicles. The fuel efficiency of this vehicle is better and the batteries can be charged with the electricity of the distribution grid by plugging into standard electric outlets next to on-board electricity generation. Therefore PHEVs offer important fuel flexibility [4].
PHEV can be driven in electric-only mode with full power. Therefore PHEV may have a larger battery and a more powerful electric motor compared to a HEV, but still their range is very limited [5].
There are several barriers to be overcome for the successful commercialisation of the PHEV. The storage of the electrical energy is the most difficult part of the vehicles. More in particular, the batteries are the limiting factor. PHEV would likely cost more than HEV because of the cost for the extra batteries. There are two main advantages. Because of the extra batteries the ICE can be more downsized. Contrary to fuel cell electric vehicles, the infrastructure requirements for PHEVs are mild and existing.
A strategy could be to recharge the batteries at night by the distribution grid, so the driver can start the day with a fully-charged battery to fulfil a part of his driving needs. During night-time, there are some troughs in the electricity demand. The demand profiles can be elevated by the off-peak recharging of vehicles [6] which would enhance the general efficiency of power plants. Nuclear plants and some coal-fired plants generate a steady flow regardless of the demand and therefore, the off-peak charging would be helpful. It is also possible to reduce the unit cost for electricity. The efficiency of the charging will be depending on the efficiency of the grid and of the existence of cleaner and efficient power plants.
Sometimes, periodically recharging of the batteries during the day is necessary. There is the availability of fast or slow charging at work destinations or other locations. The reload time is important because this determines the size of the battery charger. For a quick reload during the daytime, high power fast recharging techniques are required. The charging techniques influence the lifetime of the battery, energy efficiency and maintenance.

2 General overview: trends to 2030

This paragraph describes the trends to 2030 for the transport sector.

2.1 The Belgian vehicle fleet

The European Commission uses for nearly a decade the TREMOVE model [1] to support its environmental transport policy. 21 European countries are modelled and the model can also be used for an individual country. In the model, there is a vehicle stock module, an emission module, a life cycle module and a welfare module.
TREMOVE has determined the evolution of the composition of the Belgian fleet of passenger vehicles for the period 2005-2030 (Table 1) based on a simulation of the consumer behaviour for the business as usual scenario. New cars are purchased using the total cost per kilometre, the size and the performance of the motor. The figures for the period 1995-2004 are coming from Febiac.
At 2005, half of the Belgian market exists of gasoline ICE CVs and the other half of diesel ICE CVs. The fleet of both diesel and gasoline HEVs will be enormously increased by 2030 up to respectively 1 440 000 and 660 000 vehicles which is 35% of the diesel vehicles and 30% of the gasoline vehicles. For new technologies, such as HEVs, it takes some time to penetrate the market, but they will have an important share after some years. HEVs will take over around 7% of the market by 2010 and around 30% by 2030. At 2010, the amount of diesel and gasoline HEVs is equal and contains both 90 000 vehicles. The compressed natural gas (CNG) vehicles will have a share of 15% by 2030. Fuel cell electric vehicles are not taking into account due to their uncertainty about producing and cost.

Table 1: Number of vehicles x 1000 [1]

	1995	2000	2005	2010	2015	2020	2025	2030
gasoline HEV	0	0	0	90	240	380	570	660
diesel HEV	0	0	0	90	380	660	950	1140
gasoline CV	2840	2740	2460	2180	1890	1700	1510	1510
diesel CV	1420	1890	2460	2740	2550	2360	2180	2080
CNG vehicle	0	0	0	190	520	760	850	950
total	4260	4640	4920	5300	5580	5860	6050	6340

2.2 The fuel economy of hybrid electric vehicles

Table 2 gives an idea of the efficiency of HEVs for the period 2003-2050 [7]. The introduction of starter-alternator systems is expected in the period of 2003-2015. Some modes have mild gasoline hybrid engines and light duty vehicles

(LDV) have mainly full hybrids. There is also an initial diffusion of diesel hybrids in buses, minibuses and freight trucks. The next fifteen years are characterized by a higher penetration of mild hybrids even on small vehicles and the wide diffusion of full hybrids on large vehicles. Minibuses and (medium) freight trucks are expected to have a larger share as well. The ICE improves in light hybrids and slightly less for mild and full hybrids.

Table 2: Fuel economy (Litres of gasoline equivalent/100km) [7]

	2003-2015	2015-2030	2030-2050
full hybrids, gasoline LDV	4.1-7.4	3.9-7	3.7-6.6
mild hybrids, gasoline LDV	4.5-8	4.1-7.4	3.9-7
light hybrids, gasoline LDV	4.9-8.8	4.6-8.3	4.3-7.7
full hybrids, diesel LDV	3.2-5.7	3.1-5.5	3-5.4
mild hybrids, diesel LDV	3.4-6	3.2-5.8	3.1-5.5
light hybrids, diesel LDV	3.7-6.7	3.6-6.5	3.5-6.3

The study of McKinsey [8] expects a consumption of 7.6 l/100 km for gasoline ICE vehicles and 6.1 l/100 km for gasoline HEVs for the year 2005. For 2020, the consumption of ICE vehicles will decrease up to 6.0 l/100 km and for hybrid vehicles up to 5.1 l/100 km.

2.3 Fuel economy of conventional diesel and gasoline vehicles

The hybrid electric vehicles must be compared with ICE CVs. Table 3 shows the fuel consumption for these vehicles. For the first period, the diesel vehicles will be equipped with a second generation common-rail. In the gasoline vehicles, there will be an increased use of variable-valve control. For the second period the turbocharged diesel engine will be downsized. The particulate filter and NO_x trap will be used more and more. Direct injection and variable-valve control will be more and more used in gasoline vehicles. Also the NO_x trap will be introduced.

Table 3: Fuel economy (Litres of gasoline equivalent / 100 km) [7]

	2003-2015	2015-2030	2030-2050
Diesel ICE vehicles	4.2-7.5	4.1-7.3	4-7.1
Gasoline ICE vehicles	5.4-9.7	5.1-9.1	4.7-8.4

2.4 The transport volumes per vehicle type

TREMOVE has determined the vehicle-kilometres per year and per vehicle type for Belgium, as shown in Table 4. MC and MP are respectively motorcycles and motorpeds and LDV and HDV are respectively light and heavy duty vehicles. The vehicle-kilometres for diesel vehicles are enormously increasing in contradiction with the gasoline vehicles. TREMOVE predicts that vehicle kilometres per year by diesel vehicles increase from 61 000 up to 70 000 million. In contrast, the vehicle kilometres per year by gasoline vehicles decrease slightly from 25 000 up to 23 000 million (Table 4)

Table 4: Transport volumes (1000 million vehicle-km/year) [1]

	1995	2000	2005	2010	2015	2020	2025	2030
CNG vehicle	0	0	0	2	6	9	10	11
gasoline vehicle	34	30	26	25	23	21	22	23
diesel vehicle	34	45	55	61	62	66	68	70
MC-MP	2	2	2	2	2	2	2	2
LDV	4	5	5	5	6	6	6	6
HDV	6	8	8	8	9	9	9	11
coach, bus	1	1	1	1	1	1	1	1
total	80	91	96	102	109	114	118	124

2.5 The CO_2 emissions of hybrid electric vehicles

Under the Kyoto Protocol of the United Nations, the European Commission has decided to reduce greenhouse gases. CO_2 is one of the most important greenhouse gases. Transport plays a major role in emitting CO_2 gasses. The European Automobile Manufacturers Association (ACEA) and the European Commission have a voluntary agreement to limit the amount of CO_2 emission for new passenger vehicles sold in Europe. The target of the agreement is to achieve of level of 140 gram CO_2 per km by 2008 and a level of 120 gram CO_2 per km by 2012. These levels are average levels for the emissions. The automobile manufacturers are not reducing CO_2 emissions fast enough. Because the ACEA will not achieve these levels, the European Commission is working on a proposal for a legally binding commitment [9, 10]. Table 5 gives the CO_2 emissions of HEVs for the period 2003-2050.

Table 5: CO_2 emissions, well to wheel (g/km) [7]

	2003-2015	2015-2030	2030-2050
full hybrids, gasoline LDV	115-206	109-195	103-184
mild hybrids, gasoline LDV	125-224	115-205	108-194
light hybrids, gasoline LDV	138-247	128-230	119-214
full hybrids, diesel LDV	95-171	90-165	89-159
mild hybrids, diesel LDV	100-179	96-172	92-165
light hybrids, diesel LDV	111-199	108-193	105-188

2.6 The CO_2 emissions of conventional diesel and gasoline vehicles

The conventional vehicles will also getting cleaner in the next decades due to better fuel efficiency, filters and catalysts. Table 6 gives an idea of the expected CO_2 emission.

Table 6: CO_2 emissions, well to wheel (g/km) [7]

	2003-2015	2015-2030	2030-2050
Gasoline ICE vehicles	151-270	141-253	131-235
Diesel ICE vehicles	125-223	121-218	118-212

2.7 The CO_2 emissions of the power plants in Belgium

PHEVs can be charged by the distribution grid. It is not correct to assume that this energy is not related with CO_2 emissions. The electricity of the distribution grid is (mostly) generated by the power plants in Belgium who also emit CO_2 during their production (Table 7).

Table 7: CO_2 emissions of the power plants in Belgium [2]

year	CO_2 emissions (baseline scenario) [t/GWh$_e$]	CO_2 emissions (Bpk15 scenario) [t/GWh$_e$]	CO_2 emissions (Bpk15n scenario) [t/GWh$_e$]
2010	212.0	195.3	186.5
2015	212.5.	170.0	156.8
2020	213.0	144.7	127.0
2025	304.0	119.3	97.3
2030	395.0	94.0	67.6

These emissions are calculated with the PRIMES model [2]. The first scenario is the baseline scenario where there is no post-Kyoto reduction limit and where a decommissioning of nuclear plants takes place. In the Bpk15 scenario, Belgium reduces its energy CO_2 emissions by 15% in 2030 compared to the 1990 level and the decommissioning of nuclear plants take place. In the Bpk15n scenario reduces Belgium its energy CO_2 emissions by 15% in 2030 compared to the 1990 level. There is a lifetime extension of existing nuclear plants and the possibility to have one new nuclear unit of 1700 MW after 2020.

3 Electrical consumption

3.1 Approach

The aim of this paragraph is to determine the amount of electrical energy of the distribution grid that is needed to charge the batteries of the PHEV so that the daily mileage of the driver can be fulfilled. This amount of electrical energy can be compared with the total electricity consumption in Belgium. The period 2005-2030 will be examined and will be narrowed to 2010-2030 because the HEVs breakthrough is not significant until 2010.

Table 2 gives the fuel consumption of HEVs. The batteries are charged through on-board electricity generation using ICEs fuelled with diesel or gasoline. For a PHEV, not all the electrical energy for recharging is generated on-board by converting gasoline or diesel, but the batteries can be charged with electrical energy from the distribution grid. This reduces the fuel consumption and the fuel cycle emissions because power plants may have lower emissions than vehicles. The size of the battery determines the maximum amount of energy the battery can store.

It is difficult to predict the proportion of electric driving and the proportion of driving on diesel or gasoline of a PHEV. This depends from vehicle to vehicle and from trip to trip. Instead of taking one number, we have opted for taking an interval for the ratio going from 20% up to 90% and to investigate the sensitivity.

This gives us the possibility to calculate the electrical energy a PHEV consumes per day on average depending on the ratio of electric driving. Taking into account that the battery can store a maximum of electrical energy, the electrical energy delivered by the distribution grid is limited and can be determined.

Table 1 gives only information about the HEV and not about PHEV, but PHEV can be taken as an option within the HEV.

3.2 Results

PHEVs are usually full hybrid electric vehicles. The efficiency of the charger is also important. The battery will be charged with an efficiency of 90% and will be discharged with an efficiency of also 90%. The distribution and transport losses are also taken into account. The average driven kilometres per vehicle type per day are calculated. There is no reason to assume that HEVs will drive fewer or more kilometres compared to conventional vehicles. Assuming that these vehicles drive 50% of the time electric, the daily and yearly electrical consumption of these vehicles is shown in Table 8.

Table 8: The electrical consumption of PHEVs

		daily km [km/ day-vehicle]	capacity [kWh/ vehicle-day]	Electrical consumption [TWh/year]
2010	gasoline PHEV	30.2	6.02-10.87	0.22-0.40
	diesel PHEV	59.1	9.20-16.38	0.34-0.60
2015	gasoline PHEV	29.6	5.62-10.08	0.55-0.98
	diesel PHEV	58.0	8.75-15.52	1.35-2.39
2020	gasoline PHEV	27.7	5.25-9.42	0.81-1.45
	diesel PHEV	59.9	9.03-16.03	2.42-4.29
2025	gasoline PHEV	29.0	5.50-9.87	1.27-2.28
	diesel PHEV	59.5	8.98-15.93	3.46-6.14
2030	gasoline PHEV	29.0	5.23-9.33	1.40-2.50
	diesel PHEV	59.6	8.70-15.65	4.02-7.24

The maximum electrical consumption for diesel PHEVs is 16.38 kWh and for gasoline PHEV 10.87 kWh in the year 2010. This means that the storage capacities of the batteries in PHEV have a maximum energy capacity of 16.38 kWh. The Toyota Prius has a battery capacity of 2 kWh, but the converting PHEV kits have battery capacities ranging from 5 to 12 kWh [11] and the prototype of the DaimlerChrysler Sprinter has a capacity of 14.4 kWh, using Lithium-ion batteries [12]. For gasoline PHEVs, it is possible to drive 50% electric, but for diesel PHEVs, at this moment, this is difficult. It is important to notice that the daily driven kilometres differ from year to year and from type of fuel (gasoline or diesel). Gasoline PHEVs will need smaller battery capacity because of the lower vehicle-kilometres per year compared to diesel vehicles.

The total consumption of the HEVs for Belgium, assuming that the fleet of hybrid vehicles will exist of 100% PHEVs is giving in Table 8. These figures can be compared with the amount of generated electricity in Belgium to give an idea of the percent they take of the yearly consumed electricity.

Table 9 shows the prediction of the Commission 2030 [2] about the generated electricity according to the different scenarios.

The Commission 2030 [2] predicts an electrical consumption for the baseline scenario given in the second column of Table 9. The consumption according to the Bpk15 and Bpk15n scenarios are given in respectively the third and fourth column and are respectively 0.2% and 9.6% higher in 2030 compared to the baseline scenario. The Bpk15 scenario equated with the baseline scenario for the electrical consumption.

Table 9: Generated electricity in Belgium [2]

	Total electrical consumption (baseline scenario) [TWh]	Total electrical consumption (Bpk15) [TWh]	Total electrical consumption (Bpk15n) [TWh]
2000	80	80.0	80
2005	85	85.0	86.8
2010	90	90.1	93.5
2015	95	95.1	100.3
2020	100	100.2	107.
2025	105	105.2	113.8
2030	110	110.2	120.6

This information gives us the possibility to determine the proportion of the electrical consumption for charging PHEVs to the total electrical consumption in Belgium and is given in Table 10.

Table 10: The electrical consumption of PHEVs compared with the electrical consumption in Belgium

		ratio for baseline scenario [%]	ratio for Bpk15n scenario [%]
2010	gasoline PHEV	0.3	0.3
	diesel PHEV	0.5	0.5
2015	gasoline PHEV	0.8	0.8
	diesel PHEV	2.0	1.9
2020	gasoline PHEV	1.1	1.1
	diesel PHEV	3.4	3.1
2025	gasoline PHEV	1.7	1.6
	diesel PHEV	4.6	4.2
2030	gasoline PHEV	1.8	1.6
	diesel PHEV	5.1	4.7

The electrical consumption for charging PHEVs will take in the worst case about 5.1% of the total electrical consumption in Belgium which is a not negligible proportion. It is also important to remark that all this energy will be taken of the low voltage grid, for example at the standard electric outlet in the garage.

Table 10 assumed a constant electric drive proportion of 50%. Another interesting aspect of this study is to vary the electric drive proportion. A limit or boundary condition for this variation is the amount of energy the batteries can store, assuming that PHEVs will only be charged at night and that there is no (quick) charge possibility during the day.

Figure 1 and Figure 2 give the electrical consumption of PHEVs for the period 2010-2030 for a variation of driving proportions going from 20 up to 90%.
Figure 1 shows the electrical consumption for diesel PHEVs. Over the decades, the electrical consumption is going down for the same proportion of electric driving. The electrical consumption is depending on the fuel consumption and the daily driven kilometres. The decrease of the electrical consumption is mainly because of the improved fuel economy. The daily driven kilometres (Table 8) are slightly increasing and thus annul a little the improved fuel economy.

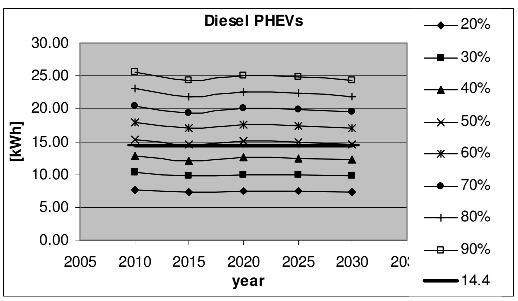

Figure 1: Electrical consumption of diesel PHEVs in function of the proportion of electric drive

Figure 2 shows the electrical consumption for gasoline PHEVs. Gasoline HEVs are consuming more compared with diesel HEVs but gasoline HEVs and vehicles in general will drive fewer kilometres and therefore need less energy storage capacity for the batteries to fulfil there daily mileage. The reason for the dip in each curve is because of the dip in the vehicle kilometres (Table 4). Therefore, less energy has to be stored in the batteries.

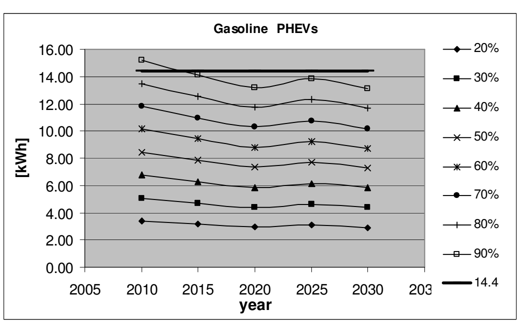

Figure 2: Electrical consumption of gasoline PHEVs in function of the proportion of electric drive

For the diesel PHEVs, the battery is the limited factor. For 50% electric driving or more of the mileage, the battery storage will probably be too small. The gasoline PHEVs nearly don't reach the limit. For gasoline vehicles, it is possible to drive the daily driven kilometres with the energy of the batteries coming from the distribution grid. It has to be noticed that these kilometres are average kilometres and that this is not possible for each driver. Some drivers will drive more kilometres and will use there vehicles as HEV which will be compensated with people who are driving less kilometres. Secondly, the limit for the battery capacity is very high because this was for a DaimlerChrysler van (light duty vehicle) and a passenger vehicle has less place insight. Some people will almost never have to buy gasoline. They would only have to charge the vehicle during the night. PHEVs could be used in essence as pure electric vehicles. The ICE will only be used to extend their driving range and to overcome the shortcomings of pure electric vehicles.
On the other hand, the storage capacity of the batteries can be extended by the year 2030, because the value of 14.4 kWh [12] is based on a prototype of PHEV of this moment.

4 Avoided CO_2 emissions

4.1 Approach

The better fuel efficiency of HEVs and PHEVs imply a reduction of CO_2 emissions. The CO_2 emissions are calculated for three different types. First, we assume that the introduction of HEVs has not been taken place, so all the HEVs will be replaced by conventional diesel and gasoline vehicles. Secondly, the CO_2 emissions for HEVs are calculated. In a third case, the HEVs are replaced by PHEVs where 50% of there driving is done by the energy stored in the battery which is charged completely by the distribution grid.
The main goal of this paragraph is to calculate the avoided emissions. Firstly, the avoided emissions are calculated by replacing the CVs by HEVs and secondly the HEVs are replaced by PHEVs. These emissions are calculated with the aid of Table 5, Table 6 and Table 7.

4.2 Results

Table 11 and Table 12 show the CO_2 emissions for the different types of vehicles and scenarios. The CO_2 emissions of the distribution grid are given in Table 7. Depending on the scenarios, the emissions of the vehicles will differ. For the PHEVs, 50% electric driven is assumed where the energy is coming from the distribution grid by charging at night produced by the power plants. This gives the three possibilities for the PHEVs.

Table 11: CO_2 emissions for CVs and HEVs

		CO_2 emissions hybrid vehicles [Mton/year]	CO_2 emissions conventional vehicles [Mton/year]
2010	gasoline vehicle	0.11-0.20	0.1-0.3
	diesel vehicle	0.18-0.33	0.2-0.4
2015	gasoline vehicle	0.28-0.51	0.4-0.7
	diesel vehicle	0.72-1.33	1.0-1.8
2020	gasoline vehicle	0.42-0.75	0.5-1.0
	diesel vehicle	1.30-2.38	1.7-3.1
2025	gasoline vehicle	0.66-1.18	0.9-1.5
	diesel vehicle	1.86-3.41	2.5-4.5
2030	gasoline vehicle	0.72-1.29	0.9-1.6
	diesel vehicle	2.21-3.94	2.9-5.3

Table 12: CO_2 emissions by PHEVs

		CO_2 emissions PHEV (baseline scenario) [Mton/year]	CO_2 emissions PHEV (Bpk15 scenario) [Mton/year]	CO_2 emissions PHEV (Bpk15n scenario) [Mton/year]
2010	gasoline vehicle	0.15	0.15	0.14
	diesel vehicle	0.24	0.23	0.23
2015	gasoline vehicle	0.38	0.34	0.33
	diesel vehicle	0.96	0.87	0.84
2020	gasoline vehicle	0.56	0.47	0.45
	diesel vehicle	1.72	1.46	1.40
2025	gasoline vehicle	1.06	0.70	0.65
	diesel vehicle	2.95	1.96	1.84
2030	gasoline vehicle	1.36	0.71	0.65
	diesel vehicle	4.03	2.13	1.96

For all the cases, the CO_2 emissions for gasoline vehicles are lower compared to diesel vehicles. The differences between the scenarios are clearly at the period 2030.

Table 13: Avoided emissions

		HEVs - CV [Mton]	HEVs PHEVs (baseline scenario) [Mton]	HEVs PHEVs (Bpk15) [Mton]	HEVs PHEVs (Bpk15n) [Mton]
2010	gasoline vehicle	0.05	0.01	0.01	0.02
	diesel vehicle	0.08	0.02	0.03	0.03
2015	gasoline vehicle	0.12	0.02	0.05	0.06
	diesel vehicle	0.34	0.07	0.16	0.18
2020	gasoline vehicle	0.17	0.02	0.11	0.13
	diesel vehicle	0.61	0.12	0.38	0.44
2025	gasoline vehicle	0.27	-0.15	0.22	0.26
	diesel vehicle	0.87	-0.32	0.67	0.79
2030	gasoline vehicle	0.28	-0.36	0.30	0.35
	diesel vehicle	1.02	-0.95	0.94	1.11

The emissions of the conventional vehicles are higher compared to HEVs. The main reason here for is that HEVs are working most of the time close the optimum working point. Therefore, the fuel efficiency is much better and the CO_2 emissions will decrease. The PHEVs are doing one half of their daily driving needs electric with the energy of the battery which is coming for the distribution grid. One very important issue is the emissions of the Belgian power plants. The emissions of the Belgian power plants to produce the electricity to charge the batteries for the PHEVs can not be neglected and must be added by the emissions of the PHEVs in Table 12.

For the baseline scenario, the avoided emissions are slightly negative which means that the HEVs will consume less compared to the PHEVs. This means that the CO_2 emissions of the Belgian power plants are too high. For the other two scenarios, where the Kyoto restrictions are taken into account, the result is positive.

5 Economic evaluation

For the economic part, the electricity cost for recharging is compared with the fuel cost.

5.1 Approach

Assuming that 50% of the daily driven kilometres by PHEV will be electric and that the batteries are large enough to provide all the electrical energy, the cost price for charging during the night will be calculated. The cost price of the electricity will be compared with the cost price of the fuel if the vehicle can not be plugged in and all the daily mileage must be driven by the

engine (in which the engine can drive the wheels or reload the batteries).
The baseline scenario [2] predicts that the price of crude oil will increase to 60 $/barrel in 2030, now being 55 $/barrel. The scenario of the soaring prices expects the price of crude oil to increase until 100 $/barrel.

Table 14: Fuel price of gasoline and diesel [Euro]

valid from	7/03/07		20/03/07	
	gasoline 98 oct 50ppm		Diesel 50 ppm	
Price ex-refinery	0.3682	26.88%	0.3632	34.62%
Distribution- & Storage costs	0.1568	11.44%	0.1577	15.03%
Price(excl. tax)	0.5250	38.32%	0.5209	49.66%
Excises + Energy contribution	0.6072	44.32%	0.3461	32.99%
Price (excl. VAT)	1.1322	82.64%	0.8670	82.65%
VAT	0.2378	17.35%	0.1821	17.36%
consumer price VAT incl.	1.370	100.00%	1.049	100.00%

Table 14 gives the current prices of gasoline and diesel in Belgium together with their splitting up. The price of crude oil at 19 March 2007 is 56.73 $/barrel.

With Table 14 and the current crude oil price, the minimum and maximum fuel price can be calculated (Table 15).

Table 15: Prices of the fuel

		minimum fuel price [euro/l] (baseline scenario)	maximum fuel price [euro/l] (baseline scenario with soaring fuel prices)
2005	gasoline	1.42	1.42
	diesel	1.09	1.09
2010	gasoline	1.44	1.65
	diesel	1.11	1.26
2015	gasoline	1.47	1.88
	diesel	1.13	1.44
2020	gasoline	1.50	2.11
	diesel	1.15	1.62
2025	gasoline	1.52	2.35
	diesel	1.17	1.80
2030	gasoline	1.55	2.58
	diesel	1.19	1.98

The prices of the electricity are also important for PHEVs. In general, there are two different tariffs. For one tariff, the energy meter makes a difference between day time and night time and set also two different prices. The other meter makes no difference between day time and night time and sets the same price for both. The electricity prices exist of the energy price, the distribution and transport prices. The two last prices are depending of the grid managers. For this calculation only the largest managers are taken into account. In that way, a weighted average can be calculated for the distribution and transport prices. A general price can be calculated on the basic of the distribution of 1 and 2-hours meters [13]. The price for electricity is then 0.124 Euro/kWh.

5.2 Results

Table 16 shows the fuel cost for the different vehicle types.

Table 16: Average fuel cost per vehicle type (euro/year-vehicle)

		Conventional vehicle (baseline scenario)	conventional vehicle (baseline scenario with soaring prices)	HEVs (baseline scenario)	HEVs (baseline scenario with soaring prices)	PHEVs (baseline scenario)	PHEVs (baseline scenario with soaring prices)
2010	gasoline	931	1064	915	1045	883	949
	diesel	1800	2057	1061	1213	1176	1251
2015	gasoline	905	1159	865	1108	828	950
	diesel	1692	2167	1024	1312	1124	1268
2020	gasoline	861	1217	823	1164	782	952
	diesel	1778	2513	1077	1522	1170	1393
2025	gasoline	917	1415	877	1353	826	1064
	diesel	1798	2773	1089	1679	1173	1468
2030	gasoline	910	1517	845	1408	789	1071
	diesel	1688	2813	1082	1804	1126	1487

For the whole period, the fuel cost for HEVs is of course less compared to conventional vehicles for both scenarios because of the better fuel efficiency. The comparison of the HEVs and PHEVs for the baseline scenario gives a difference between gasoline and diesel vehicles. The fuel price for diesel HEVs is lower compared to diesel PHEVs and for gasoline vehicles, the opposite is true. For the baseline scenario with soaring prices, the PHEVs fuel cost is lower compared to the HEVs fuel cost. The cost of the required infrastructure is important. A study [14] estimates that an on-board charger and cable capable of 1.0 kWh/h, compatible with 120 V would cost about €370. A fast charger with a cable of 5.7 kWh would cost about €800.

But the charging rate is too slow for refueling stations. The very fast chargers are very expensive and are only economic if they can sell electricity at low enough prices to beat gasoline prices because PHEV can use both.

6 Conclusion

Depending on the scenarios, the charging of the batteries of PHEVs will take a not negligible part of the total electrical consumption in Belgium. It is important to notice that this is the global consumption and this does not tell anything about the impact on the local grid. Diesel PHEVs will be able to drive on average 50% electric and gasoline will be able to drive almost 100% electric on average because of the lower vehicle-kilometres. The emissions of HEVs and PHEVs are lower compared to CVs because of the better fuel efficiency and the lower emissions of the power plants. The fuel cost of HEVs is lower compared to CVs because of the better fuel efficiency. It is difficult to predict the electricity price for the future.

7 References

[1] S. Logghe, B. Van Herbruggen, B. Van Zeebroeck, *Emissions of road traffic in Belgium*, Transport & Mobility Leuven, January 2006.

[2] Commission Energy 2030, *Belgium's energy challenges towards 2030, preliminary report*, November 2006.

[3] TNO Automotive, *Overview of developments in the field of electric hybrid and fuel cell vehicles and technologie*s, Netherlands, 2003.

[4] A. Raskin, S. Shah, *The emerge of hybrid electric vehicles,* AllianceBernstein, 2006

[5] M. Anderman., *The challenge to fulfil electrical power requirements of advanced vehicles*, Journal of Power Sources, 127(2004), pp 2-7.

[6] J. Van Mierlo., *Simulation software for comparison and design of electric, hybrid electric and internal combustion vehicles with respect to energy, emissions and performances*, Phd, Vrije Universiteit Brussel, June 2000

[7] International Energy Agency, *Energy Technology Perspectives, Scenarios and strategies to 2050*, chapter 5, France, 2006.

[8] McKinsey, *Drive, The future of automotive power*, 2006

[9] Agence France Presse, *EU to introduce legislation as car makers fail on emission targets,* Brussel, November 2006.

[10] Transport & Environment, *How clean is your car brand?*, Brussels, October 2006.

[11] http://www.greencarcongress.com/2006/02/hymotion_unveil.html

[12] DaimlerChrysler, *Overview of DC ZEV activities*, ZEV Technology Symposium, September 2006.

[13] VREG, *Rapport van de Vlaamse reguleringsinstantie voor elektriciteits-en gasmarkt*, Brussel, October 2006.

[14] S. Plotkin, *Grid-Connected Hybrids: Another Option in the Search to Replace Gasoline*, TRB Annual Meeting, 2006.

[15] Eurelectric, *Demand of Electricity Transport Part I automotive*, 2006.

[16] J. Van Mierlo,G. Maggetto,Ph. Lataire, *Which energy source for road transport in the future? A Comparison of battery, hybrid and fuel cell vehicles,* Energy Conversion and Management, 2006, vol 47, pp 2748-2760.

[17] VREG, *Rapport van de Vlaamse reguleringsinstantie voor elektriciteits-en gasmarkt*, Brussel, October 2006.

Authors

Kristien Clement received the M.S. degree in electro-mechanical engineering in 2004 with specialization Energy. Currently she is working toward her Ph.D in electrotechnical engineering at the K.U.Leuven division ELECTA.

Koen Van Reusel received the M.S. degree in electrical engineering in 1985 from the K.U. Leuven, Belgium. Currently he is chair holder of the Interuniversity ELECTRABEL Chair for electroheat. He was with LABORELEC, for more than 10 years. During this time he was responsible for feasibility studies on electroheat applications in industry. From 1998 to 2003, he developed a technical service "Power Quality" for the industrial customers of ELECTRABEL. His actual research interests are in the use of electricity for industrial heat processes, numerical modelling of electroheat processes, the impact on "Power Quality" of electricity appliances, and "Electromagnetic Processing of Materials".

Johan Driesen (S'93–M'97) was born in Belgium in 1973. He received the M.Sc. and Ph.D. degrees in electrical engineering from Katholieke Universiteit Leuven (K.U. Leuven), Leuven, Belgium, in 1996 and 2000 on the finite element solution of coupled thermal-electromagnetic problems and related applications in electrical machines and drives, microsystems, and power-quality issues. Currently, he is an Associate Professor with K.U. Leuven and teaches power electronics and drives. In 2000–2001, he was a Visiting Researcher with the Imperial College of Science, Technology and Medicine, London, U.K. In 2002, he was with the University of California, Berkeley. Currently, he conducts research on distributed generation, including renewable energy systems, power electronics and its applications (e.g., in drives and power quality).