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Plug-in Hybrid Vehicles

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1. Introduction

The plug-in hybrid vehicle (PHEV) represents the reaction of automotive industry on the green policy, to reduce the pollutions and the fossil fuels consumption in transport. The oil price is permanently rising and the oil import makes unpleasant dependence of the national economy on the non-stabile countries, because the road transport is nowadays completely dependent on the oil fuels. The electric drive is ready for use in the vehicles many years, it is optimal for control and it offers the maximal efficiency, but there is no suitable battery available in this time for all the day vehicle energy supply. But most of cars in household are typically used in common commutation cycle, with average daily portion under 50km and they are only occasionally used for longer trips in weekends or holidays. For such range is the battery available with acceptable weight and price. If users do not like to hold and care two cars, the electric one for commutation and the second one with petrol engine for longer trips, the PHEV is an optimal solution, combining both drives and the suitable cooperation between both power sources can give additional profit; also many materials and components for the second car - body, wheels and suspension - are saved. However it must be said that having better battery (or similar electrical energy storage device), the presence of generator and internal combustion engine (ICE) is not necessary and the PHEV would be reduced to the much simpler battery operated vehicle (BEV), although the running engine produces some “free” heat which can be with advantage used for air-conditioning. The green energy production from renewable power sources or from nuclear power plants grows up and the night charging can solve the oil fuels reduction in the road transport.

2. History of EV and HEV

In the beginning of auto-mobility the electric drive was more successful, than engines with internal combustion. The previous steam engines, very famous from railway locomotives, were also not suitable for mobile lightweight applications, due to their big mass and the need of water, which was permanently wasted in open system without condensation.
In the road passenger transport for very limited distance (due to low speed on roads for horses) and for the sport activities was electric motor (EM) with a cheap lead acid battery and simple speed control very reliable and easy operable. Looking in the historical records, the first vehicle over 100km/h speed limit was electric vehicle and also the number of registered vehicles with EM was equal to other kinds of drive. Only after the Ford’s mass production of cheap vehicles with engine the ratio of electric vehicles decreases. Then with

better roads, growing speed and operating range consequently, the low battery capacity and the slow long-lasting charging process beat in competition the electric vehicle in the road transport. Only the cable supply was suitable to compete in the city transport (trolleybus) and the battery supply remained only in low speed local transport, like door to door milk and mail delivery, shipping in the production halls or in the railway stations, and in the last decade also some golf carts and neighbourhood electric cars can be find in the market offer.

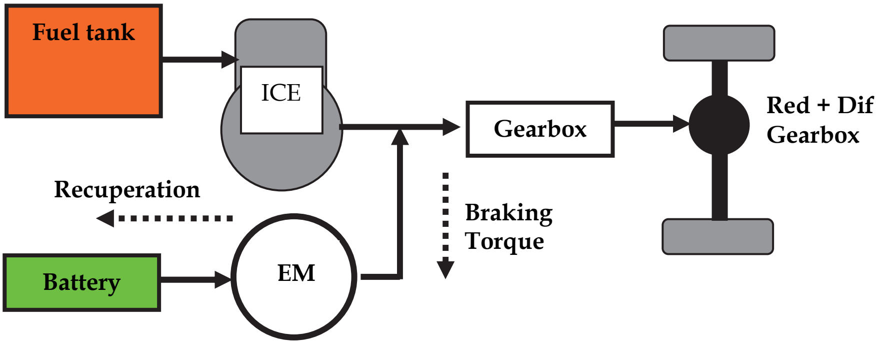

Fig. 1. Typical configuration of common hybrid vehicle with parallel power flow

Hybrid vehicles (HEV) with combination of engine and EM bring back the electric drive into vehicle traction. They are on the market over ten years and their second generation is offered now. First HEV were only from the Japanese production, but in last few years every automotive production group presents at least one car with electric hybrid drive. Such vehicle is certainly more expensive in manufacturing, but the advantage of HEV is its reduced fuel consumption, primarily in the city cycle with low average speed, in which the standard ICE vehicle has higher consumption (lower mileage), comparing with land transport at much higher speed. Out of city the fuel savings are not detectable.

3. Hybrid vehicles

The typical HEV (Fig.1) has only low power EM, which assists in the phase of vehicle acceleration and again in the braking, when it can recuperate the part of kinetic energy into battery for the next acceleration. The efficiency of this cycle (braking – acceleration) is not very good and about 50% of energy is lost, but in often repeating of this cycle at each traffic lights, the fuel saving is important. The energy in one cycle is not big; therefore only small battery can be used. The battery life in the number of cycles is very important, because it is not acceptable to change this battery each month. Fortunately, the reduced depth of discharge (DOD) extends the length of lifetime very much and this low ratio between the energy of one cycle and the energy of the battery is the way, how to use one battery pack up to five years with total number of cycles over 100 000.

The HEV principal scheme can be followed in Fig.1, where it can be observed the parallel power ways from both torque sources to the wheel. The EM can work not only in motor run, when it produces the torque and mechanical power from electric energy, but it can be easily switched into generator run, when the mechanical power from kinetic energy of vehicle is changed into electric energy, recuperated back to battery. The advantage of EM presence is not only the energy recuperation, but also the torque production at any speed, like it was at old steam engines. No kind of ICE is able to produce the torque at zero speed and moreover there is some minimal value of crankshaft speed, called idle run, under which the ICE stops. To keep the ICE in the idle run needs also some fuel and in city transport the standing at the crossroads is very often and very long lasting. The engine stopping at any occasion and its automatic starting connected with touch of clutch pedal, known as STOP-START system is also effective, but it does not eliminate the energy wasting in brakes and the fuel consumption for acceleration. Also the clutch wear is much higher than in the case of vehicle accelerating by EM torque.

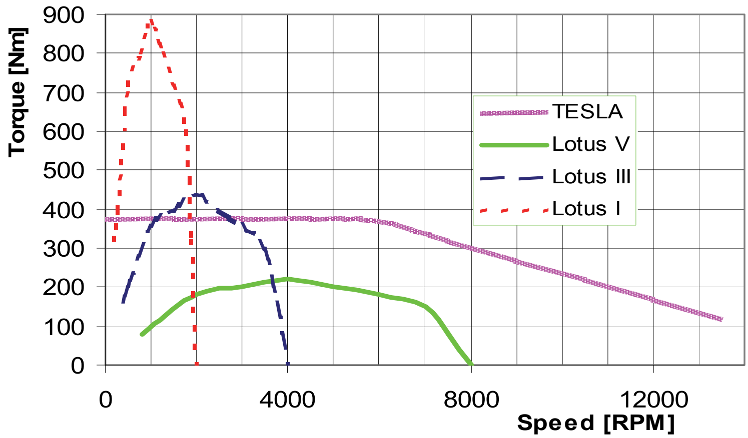

Fig. 2. Mechanical characteristics of EM vs. ICE with gearbox (r_{III}=2, r_V=4)

3.1 EM advantages

The comparison of EM and ICE mechanical characteristics is in Fig.2 and it can be said here, that any EM can have the same characteristic if it is supplied from suitable inverter. Each EM can be for short time overloaded, when increased current gives increased torque and the torque is to disposal from zero speed. Also each kind of EM can recuperate the energy working in generating mode, the negative (braking) torque reverses the current back to the source. The speed gap between the zero and idle run speed of ICE can be reduced using the variable-ratio gearbox. In the gearbox, when the speed is reduced, the torque grows up inversely. The higher is the gear ratio, the lower is the speed and the higher is the torque keeping the same power (neglecting losses). The mechanical power is given by:

$$P = T\,\omega \tag{1}$$

where **T** is the torque in Newton-meters and **ω** is angular speed in radians per second. The common technical unit of speed **n** is revolve per minute, the transformation formula is:

$$\omega = (2\,\pi\,/60)\,n \approx n/10 \tag{2}$$

The gear ratio, according to (1) gives:

$$r = n_2/n_1 = T_1/T_2 \quad (3)$$

From this mathematics and from Fig.2 there is evident, that at high speed the ICE has always enough power, therefore it needs the help from EM2 primarily in the area of low speeds, where the power is also small as results from (1). Low power EM and low power battery are not able to drive the vehicle at speed over 10km/h. For fully electric drive the concept must be modified.

4. Why plug-in hybrid?

Many car owner do not use the car for business travel, and they do not drive daily more than 50km. for such distance it is not necessary to spend any petrol, because this distance can be easily realized by energy from battery, but great disadvantage of electric drive is, that the "empty" battery cannot be recharged in minutes and in the case of longer trip, the safety return is not sure. Also in some rare trips during holidays etc. cannot be realized by electric vehicle that means you must have or purchase another car. All these problems are solved by serial hybrid with greater battery, which can be driven first 50km from battery only and in the case of longer trip; the engine is started and operated in the optimal efficiency work point with constant power and speed. The generated electricity is either used for motors supply or in case of low load is simultaneously stored in empty battery.
The PHEV must be able to work in electric mode only at any speed, during the short trips under the daily limit. Therefore it must have strong enough electric motor EM and this condition results in serial concept hybrid, when the ICE is not mechanically connected with wheels, because its help is not necessary (Fig.3).

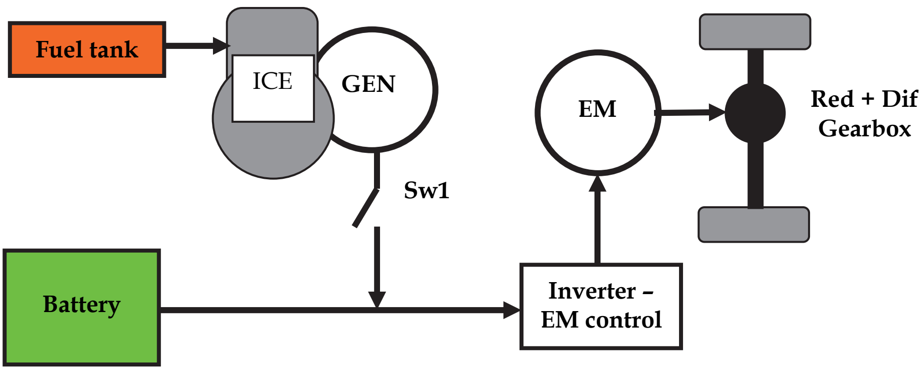

Fig. 3. Typical configuration of PHEV with serial power flow

Omitting the generating unit in Fig.3, the PHEV is reduced into the simple BEV and only the parameters of battery determine the operating range of this vehicle. The idea of hybrid concept wants to eliminate the danger of empty battery in case of some complication in traffic like detour, lost way, waiting, etc. Because the battery charging is supposed from home plug during many hours and there are no charging stations in streets, the best way how to be mobile permanently is to have the energy source for charging on the board. The

power of the charger does not have to be as big as is the EM power, because in the periods with full power both sources, generator and battery, work together.
All the mechanical energy output from ICE is converted by generator into electricity, which is typically divided between EM and battery, when EM does not work with full power. If the EM is loaded more than is the maximal power from the generator can be, then the battery must deliver the difference. It is typical in acceleration and in uphill slope, both lasts only very short time in second or minutes. The ICE has not to be so strong (maximal power) as it is in a petrol car and it can work here always near the optimal operating point (Fig.11) with maximal efficiency and minimal emissions.
It is not the new idea to have the Engine-Generator unit on board, but to develop and realise the mass production of PHEV it is a merit of American company Chevrolet (Fig.4). However their vehicle is about three or four years in prototype and they solve intensively the problem of optimal battery. The development and new inventions in this area are very fast and it is a problem to start the production of any battery, if tomorrow some principally better technology would appear.

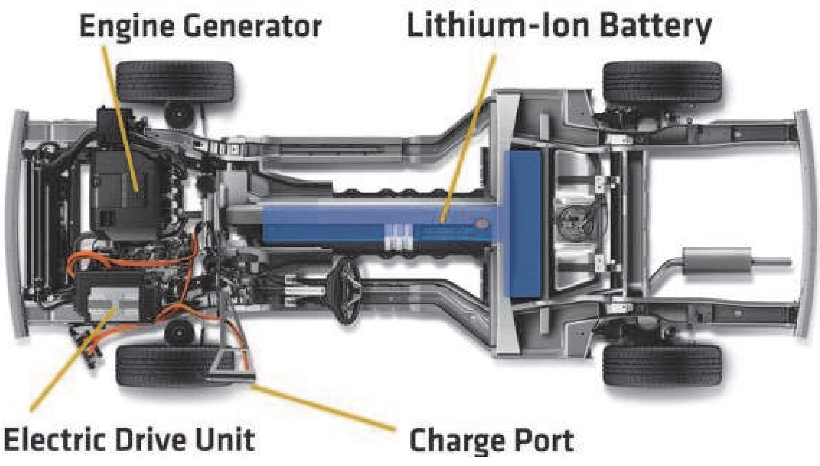

Fig. 4. Chevrolet Volt Chassis Version 2008

But it is not only the batteries production technology, also the electric motor for traction manufacturing needs new knowhow in the automotive industry. Also the manufacturers of auxiliary components must prepare new products and some problem can create the dangerous voltage in the vehicle, because the battery voltage can reach up to 300V and the motor supply voltage AC up to 400V phase to phase or DC up to 600V. It is not the same situation as is in traditional 12 or 24V and the isolation check in metallic body must be perfect. But such systems are already developed and verified in trolleybuses e.g.

5. How to dimension the PHEV components

The problem of this PHEV concept (Fig. 3) is how to reach high efficiency of all the drive train (ICE, Generator, Battery, Inverter, EM, Gear) for low power light vehicle with total mass about 1500kg. Its average power out of highway at 80 or 90km/h limit is only 5 - 10kW and the peaks are up to 100kW for dynamic drive in modern traffic. The situation in ICE cars is more dependent on the engine volume. The same model can be sold with three or more engines and each of them offers other dynamics. The power and the torque peaks are in case of ICE fix and they can only decrease due the wear, not optimal intake parameters or control, the EM is oppositely easily overload capable, of course for short time only, because the overload brings higher losses and the temperature rise consequently. Big traction machines have on their labels not only rated power but also one-hour power, which is 20 – 30% higher depending on the EM size. For vehicle acceleration in seconds the overload can be easily 100% or more, because after this period the torque and current falls down and the winding temperature also decreases back fast (with effective ventilation). From simulation in Fig.5 it can be seen, the differences between the power in acceleration and in constant speed drive for flat surface.

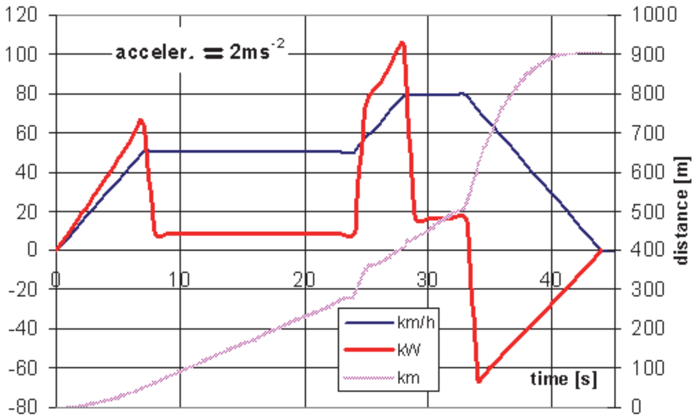

Fig. 5. Time dependence of Power, Speed and Distance for exemplar cycle

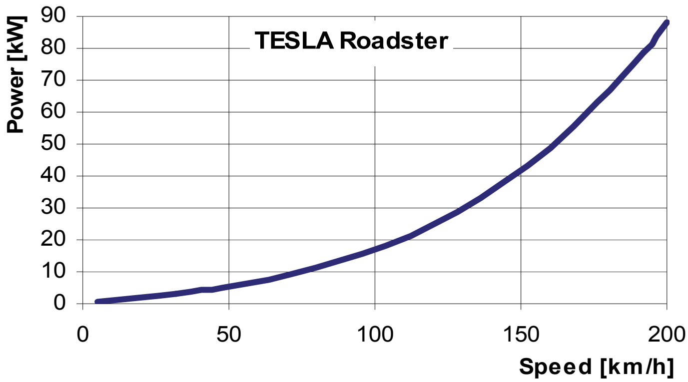

Fig. 6. Power vs. speed for EV Tesla Roadster on the plane

The dependence of the power on the vehicle speed in steady state is in the Fig. 6 for strong sport car Lotus, which is professionally remade by TESLA Cars Company for the electric drive. Because at higher speed the aerodynamic drag represent the highest force, the power grow with the speed is nearly quadratic.-Tesla Roadster has no generator, but it can be interesting to compare it with two PHEV. The selected data of two typical PHEV are in Table 1 briefly compared with top power BEV Tesla.

Mark	**Tesla**	**Chevrolet**	**Mitsubishi**
Model	Roadster	Volt	iMiEV
AC Motor	185kW	120kW	47kW
Maximal torque	375Nm	320Nm	180Nm
	Asynchronous	Asynchronous	Permanent Magnets
Maximal speed	14.000rpm		7500rpm
Voltage	370V	320V	330V
Battery	56kWh	16kWh	16kWh
Mass		180kg	
Generator	NO	53kW	---
Maximal speed	200km/h	80/140km/h	130km/h
Maximal cruise	450km	64+960km	160 km
Vehicle mass			1080kg
80% SOC			30min

Table 1. BEV and PHEV parameters comparison

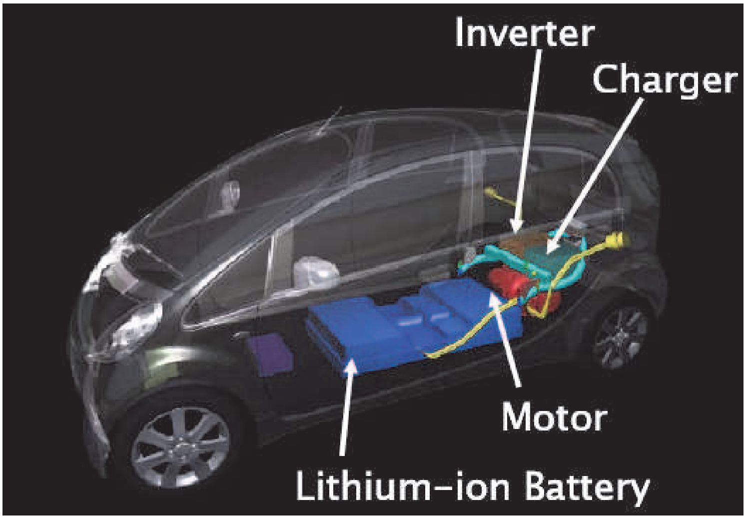

Fig. 7. Mitsubishi iMiEV through view

Chevrolet's Volt is the first series hybrid concept car shown by a major manufacturer. Its 1,0-liter (1000ccm), 3-cylinder turbocharged engine runs an on-board 53kW generator that recharges a 16kWh lithium-ion battery made of 80 four-volt cells. Main components distribution on the chassis is in Fig.4. The engine-generator has typical handwrite of car engineers and not only its size, but also its location under front hood with long exhaust pipe. Guessingly 200kg mass can be replaced by another battery with more than twice longer range. The small generator for occasional long trips could be situated in backside trunk, or in tender, which could be hired. The fix mounting of ICE needs all the servicing as standard ICE vehicle, oppositely to BEV, which needs no regular service. Because of rapid evolution in battery technology GM newly opened advanced battery laboratories (3 000 square meters).

Opel Ampera is a Twin sister car to the Chevy Volt for European market. The other leading European producers are preparing their program in EV. New producers like Fiskers, Aptera, Th!nk and many other are only the small companies involved in EV development and they can bring some revolutionary solutions, because there are strong restrictions, in big companies, based on tradition.

Mitsubishi is leading Japan Company in preparing EV with lithium batteries. Its small car iMi with ICE has its twin with electric drive, which is presently (2010) long-term tested over all Japan. The main parts arrangement can be seen on Fig.7.

5.1 Motors

The EM choice is the most important part of PHEV design. As was mentioned above the EM is easily overloadable, its power **P** depends on the voltage **U** and current **I** from the battery:

$$P = \eta\, U\, I \tag{4}$$

where **η** describes the motor efficiency. This power is equal to that one from (1). Very simplified, it can be said, that the torque is given by the EM current and the EM speed is given by voltage:

$$T = K\, \Phi\, I_a \tag{5}$$

$$U_i = K\, \Phi\, \omega \tag{6}$$

These equation are exact for DC motor, where **Φ** is magnetic flux and $\mathbf{I_a}$ is the armature (or rotor) current and $\mathbf{U_i}$ is induced voltage in the armature, which is slightly different from the terminal voltage because of the voltage drop on the internal resistances. The AC motors are more complicated, they have more phases, in case of induction (or asynchronous) motor (AM) there is no separation of field circuit and armature circuit, but it is not the main goal of this book and more can be find in any electric machines textbook. The important for motor control is how to change the voltage, and in the case of AC motors the frequency must be also changed (together with voltage), because instead of mechanical current commutation in DC rotor, the switching technology must be used to create the three phase system in converter. The output frequency **f** gives the speed of AC rotor:

$$n_s = 2\, \pi\, f \,/\, p \tag{7}$$

where **p** is the number of pole pairs. The rotor of AM is slightly slower, that difference between the speed of the rotating field $\mathbf{n_s}$ and the real rotor speed **n** is called slip and its value is typically 3 – 5%, changing with the load.

DC motors are the first kind of traction motors, and in the period before power electronics their control was only by resistance controllers and serial-parallel switching. DC/DC inverters improved the efficiency of DC motor in controlled drive, it is cheaper than the DC/AC converter, but DC motor is not so robust and it needs often maintenance due to carbon brushes.

Brushless DC is in principle the DC with permanent magnets (PM) for field creation on the rotor and static electronic inverter, instead of collector with 3 segments on the rotor; it has 3 winding terminals on the stator, supplied from the 3-legs bridge, working as a commutator. Because the rare earth PM (REPM) are very expensive and very sensitive, namely to temperature and corrosion, they find place mostly in low power (0,2 – 2kW) EM for bikes, where they are in low volume only.

In the power range 20 – 200kW for passenger cars the **induction machine** offers its perfect robustness at low price and also the standard inverter supply, which widely used in industry and also in new trams.

The switched reluctance machine (SRM) has also very robust and simple construction with no rotor winding and it can be very prospective, but it is not yet widely used. It needs special inverter, which supposes some larger volume production for a good price.

	DC Brush Type	**Brushless DC (Permanent Magnet)**	**AC (Induction)**
Peak efficiency	85 - 89	95 - 97	94 - 95
Efficiency at 10% Load	80 - 87	73 - 82	93 - 94
Max. RPM	4 000 - 6 000	4 000 - 10 000	9 000 – 15 000
Cost per shaft kW	$120 - 200	$120 - 180	$60 - 100
Relative Cost of Controller	1	3 - 5	6 - 8

Table 2. Typical Electric Motors 20 – 200kW Parameters

The survey of EM basic properties is in Table 2. It must be said here, that all parameters in this Table are valid for power range from 20 to 200kW and with growing power grows up also the efficiency and oppositely the maximal speed falls down.

AC Motor	DC Motor
Single-speed transmission	Multi-speed transmission
Light weight	Heavier at equivalent power
Less expensive	More expensive
95% Efficiency at full load	85-95% Efficiency at full load
More expensive controller	Simple controller
Motor/controller/inverter more expensive	Motor/controller less expensive

Table 3. Electric Motors Properties Comparison

Another EM properties comparison can be read in Table 3 from the drivetrain design point of view.

5.1.1 Motor volume

The volume and mass of EM is given by its torque and not by the power. Because the vehicle mass should be minimized, the EM must be designed on maximal possible speed and minimal torque consequently (1), of course with respect to efficiency and cooling ability. Therefore no direct drive without gear is optimal and there is in Fig.3 the reduction and differential gearbox between EM and wheel. Increasing the speed increases the frequency, which should not exceed 400Hz. It is better to keep the frequency under 200Hz and for two pole AM it can give the speed from (7) n_s = 12 000rpm. For the vehicle speed 144km/h = 40m/s and the wheel circumference 2m its rotation speed n_W is:

$$n_W = 60 * 40 / 2 = 120\text{rpm} \tag{8}$$

Then the total ratio between the AM and the wheel must be from (3):

$$r_{Total} = 120 / 12\,000 = 1/100 \tag{9}$$

which can be realised by 3 pairs of cogwheels minimally.

5.1.2 Motor losses

Beside of typical mechanical losses due to friction and ventilation losses, which both are speed dependent, there are in the EM specific electrical losses and these can be divided into two groups. The current depend losses, or Joule losses grow up with the square of current:

$$\Delta P_J = R_a I_a^2 \tag{10}$$

and looking in (5), they grow up with square of torque.
The other group of losses has origin in the magnetic circuit (iron) due its alternating flux. These losses can be described by formula:

$$\Delta P_{Fe} = k\, m_{Fe}\, \Phi^2 f^{1,6} \tag{11}$$

where m_{Fe} is the AC iron mass. The grow up with speed is more than linear, but if the EM has not PM field, the flux can be reduced when there is no need of full torque (5) to reduce the iron losses, but increased current results in the Joule losses grow up. The optimal flux at any speed and power can be estimated. The greatest advantage of controlled flux is at high speed and no torque run (by inertia or downhill), when the PM machine has high iron losses and they are supplied from kinetic energy of vehicle, which means they are braking the vehicle undesirably.

5.2 Battery and electrical energy storage

First EV has been built in the 1835 and 1836 respectively; the speed record 105km/h was also reached with EV in 1899 with lead acid battery. Edison tried to build EV with his Ni-Fe batteries, but without commercial success. From the year 1903 when Ford established 146km/h speed record, the petrol ruled the vehicles power supply, because of its very high energy density, which is about 36MJ/L = 10kWh/L, because the petrol density is only 0.72kg/L the mass density value is over 14kWh/kg. Also the charging power is

enormous, if filling the tank by speed 2L/s the 60L tank can be full in 30s and "supplying power" is 72MW.
Comparing with liquid hydrocarbons, the best available batteries have only 0,2kWh in one kilogram. There are some projects of better electric storage devices based on electrostatic principle, but they are only in patents and no sample has been presented. In the electrochemical batteries, the most promising are lithium-air, which can change completely the electric vehicles during next ten years. Special problem of batteries with numerous cells is their cooling (and heating) system keeping optimal temperature in all the battery pack and the voltage distribution control (charge management) for in series cells avoiding overcharging which can damage the cells with danger of explosion and fire.
Two parameters must be watched if looking for optimal battery, the energy density and the power density. Survey of suitable batteries for EV is in Table 4.
Nearly all the 20th century there was no new chemistry in secondary cells (rechargeable) introduced and only the technologies were improved in two basic batteries.
Lead-acid is wide spread battery for engines starting and for emergency power supply, the Edison alkaline battery nickel – iron Ni-Fe was slightly improved by cadmium Ni-Cd. This kind of batteries was mostly used for railway vehicles and communication technologies. The silver based chemistry Ag-Zn was able to supply electric vehicle, but the silver is not widely available (precious metal) and such batteries can be used only in very special purposes for military or space technologies.

	Lead-Acid	**(Ni-MH)**	**Lithium-Ion**
First Use (Commercial)	1859	1989	1991
Current Use (Automotive)	Traditional 12-volt batteries	For today's generation of HEV	Under development for PHEV and BEV
Strengths	Long proven in automotive use; Price	Twice the energy/ weight as lead-acid	About twice the energy content of Ni-MH
Weaknesses	Heavy; low energy/ weight ratio for EV	High cost (four times the cost of lead-acid)	Expensive until production volume
Energy density	30 - 40Wh/kg	65 - 70Wh/kg	100 - 150Wh/kg
Recyclability	Excellent	Good	Very Good

Table 4. Electrochemical Batteries Evaluation

Only the last decade of the 20th century and the new electronics devices, connected with communication and information technologies, bring the progress in the cell chemistry. The lithium ion and lithium polymer batteries replaced in few years the Ni-Mh in cellular mobile phones, notebooks and other audio and video portable players. The Ni-Cd has been also replaced in its last important area of use, which was hand-tools supply. This new batteries generation has, up to three times, higher energy density, then old chemistries, which give new possibilities for electric vehicle construction. Lithium is very promising and many new prospective chemistries with lithium are invented and developed, the survey is in Table 5.

Chemistry	Company
Doped Lithium Nanophosphate	A123
Manganese Spinel	LG / NEC
Lithium Nickel Cobalt Aluminium Oxide	Panasonic
Lithium Manganese Oxide	Hitachi
Lithium Cobalt Oxide	Commercial offer
Lithium Titanate Spinel	Altair Nano
Lithium Iron Phosphate	Lishen
Lithium Manganese Titanate	EnerDel

Table 5. Lithium Battery Chemistry Survey

The greatest problem of any battery for electric vehicle is beside its lifetime in cycles, but also its low internal electric resistance, thermal stability between -40 to +60°C, shock resistance, non toxicity, fire safety, but mostly its charging properties and its price, which can create important part of the vehicle price. For the car construction there is important also the volume and mass energy density. The cheapest chemistry is the lead acid, which his used in all cars for engine starting, but in electric vehicles only in old neighbourhood vehicles and golf cars. The modern hybrids use Nickel – Metal Hydride chemistry or Lithium, which is in strong development connected with communications and information technology produced therefore only in small cells about 2Wh. Tesla Car Company started the production of their BEV, which was designed few years ago with old technology lithium battery consisting from 6 831 small cells a little bigger than AA size (8Wh each).

5.2.1 Charging

The big problem for EV is the long time for charging the battery, which is not comfortable for permanent transport in business, comparing this time with gasoline filling, where the entire tank can be filled in the time under one minute. The calculation of the power of such filling results in megawatts. The fast charging brings not only the problems with battery cooling, but also problem with power peaks in grid, because there are no reservoirs for electrical energy (EE) similar to tanks for petrol and rapid charging results in high power peaks:

$$P_{Charge}\ [kW] = 60\ Ek\ [kWh]\ /\ t\ [min] \tag{12}$$

To charge 10kWh (which is equivalent energy of one litre petrol) in one minute, from this formula, gives the charger power 600kW (!). Because the charging is not very efficient, and more than 100kW are the losses – the heat, such rapid charging connected with energy conversion is impossible. The only hope is here the storage of EE in electrostatic field, which is not connected with energy conversion.

The rapid charging can be more effective if there is not required full charging. The partial charging is described by SOC (state of charge) in percent of full capacity. Similarly is defined the DOD (depth of discharge), which define the percent of full charge, which was taken from battery and partial discharging extends the lifetime significantly.

The energy for charging is due to chemical processes much higher, than is the energy received during discharge. It can be demonstrated on the lead acid cell, which is discharged at 2V and for each 1Ah must be recharged 1,2Ah at voltage 2,4V. From this can be easily calculated the efficiency:

$$\eta = 2 * 1 / (2{,}4 * 1{,}2) = 0{,}70 = 70\% \tag{12}$$

and similar value is valid also for the other chemistries.

5.2.2 Electrochemistry

Lead acid: The first in history secondary battery (1859), mass produced for ICE starting in all vehicles, for emergency power supply and UPS (uninterruptible power supply), it is very cheap, with number of full cycles about 400, but special construction for traction has increased number of cycles to 2000. The sulphuric acid electrolyte is very corrosive and the lead is only metal, which resists in this medium. The sealed construction and gel electrolyte allow using this battery in any position without danger of stain or effusion. Its energy density is up to 40Wh/kg, due its price it is very popular for EV drives, but the operating range is very limited and the lifetime less than 5 or 10 years respectively. Another disadvantage is the danger of sulphatizing, which can be prevented by immediate charging after run that means the battery cannot be left discharged.

Nickel or Alkaline battery: The alkalic electrolyte with NaOH or KOH is less aggressive and Edison realized the first alkaline secondary cell with Nickel and Iron electrodes so called Ni-Fe battery. Nickel cadmium Ni-Cd is an improved chemistry with higher power density. The voltage of cell is only 1.2V, but the lifetime of such battery with minimal maintenance is about 20 years. It is mostly used in railway wagons and in hand tools. The toxic cadmium was about 20 years ago (1989) successfully substituted by metal hydrides in so-called Ni-MH cells, with better energy density. This chemistry is used in Japan HEV.

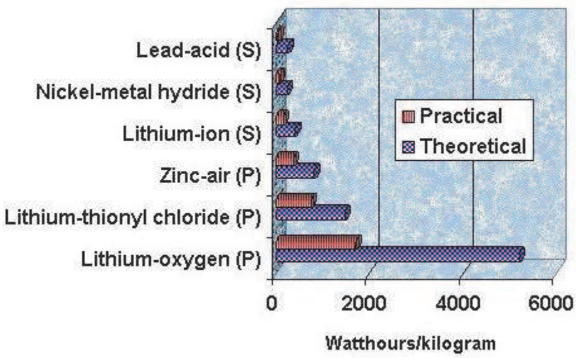

Fig. 8. Energy density in various battery chemistries

Na-MCl2 chemistry has similar parameters with Ni-MH and also Ni-Zn is from the same family with similar gravimetric density but weaker volumetric density.

Lithium battery: Very reactive lithium has highest potential, but the technology was mastered only in 1991 (by Sony). The lithium ion cells $LiCoO_2$ with rated voltage 3.75V are widely used in cellular phones and notebooks; the battery with serial connected cells must have electronic balancing system to avoid the overcharge at any cell. In last few years the big cells for traction are produced, with capacity up to 2 000Ah and new chemistry $LiFePO_4$ (lithium iron phosphate) Table 5. Comparing to lead acid the fast discharge of lithium battery does not decrease the capacity, but the energy is lower due to joule losses in internal resistance.

The theoretical specific energy of lithium thionyl battery is 1 420Wh/L (explosive TNT has 1 920Wh/L) and the theoretical specific energy of lithium-oxygen is over 5 000Wh/kg, which gives more traction energy than the petrol of the same volume or weight, if the ICE efficiency is taken into account (Fig.8).

A lithium-titanate battery is a modified lithium-ion battery that uses lithium-titanate nano-crystals on the surface of its anode instead of carbon. This applied nanotechnology gives the anode a surface area of about 100 square meters per gram, compared with 3 square meters per gram for carbon, allowing electrons to enter and leave the anode quickly. This makes fast recharging possible and provides high currents when needed

Other chemistries: In last forty years after the renaissance of EV many new electrochemical batteries have been studied, but they did not convince. High temperature NaS has good parameters, but bad maintenance, Zn-Br needs two tanks for pumping electrolyte, which stores the energy similarly as the vanadium battery, suitable more for stationary applications. Special category is Ag-Zn chemistry with super performance, but due to limited silver cannot be widespread system and it is used only in the very special military or space applications.

5.2.3 Electrostatic storage

The super-capacitors (SC) are the first revolutionary technology, which can be compared to electrochemical batteries in energy density and have much better power density, suitable for the power peaks in short time.

Quantum Battery (QB) promises the surprising energy density, it is based on the discovery of quantum effect on TiO_2 sample, measured by Swiss inventor and described in patent application. The rutile crystals, 15nm long, absorb at 180V the energy with density 8 – 12MJ/kg. It is very optimistic, but without working prototype and with the theory of photon resonance only. Author describes cheap technology with possible market price 15USD/kWh. The predicted low self-discharge (about 6,3 % per month) and long durability would be optimal for EV.

EEStore from Cedar Park, TX, also announces the promising technology of high voltage solid dielectrics super-capacitor based on thin layer (nanometers) with high permittivity barium titanate composite. In the last period the power density 1200kJ/kg is referred, which is four times more than electrochemical battery, moreover without looses and with short recharging time less than one minute. But nanotechnologies in batteries with lithium chemistry can be also competitive, as is mentioned above.

5.3 PHEV auxiliary components

As it is mentioned above, the absence of running ICE in PHEV means, there is no source of thermal energy suitable for cabin heating. The heating as well as cooling, simply all the cabin air condition can be realised by heat pump with electric drive, which must be developed for next PHEV. The heat pump usage can save significantly the spending of limited battery energy for non traction purposes.

There is also no mechanical drive of powered steering pump, powered braking without running ICE and the modern car is supposed to have all these facilities, which must be realised by local electric drives.
The lighting, dashboard and cabin electronics need low voltage supply, which must be also realized by power electronics DC/DC inverter, instead of rotating generator.
All here listed components that must be developed for PHEV can later serve also for BEV, when better battery will be available, but these components design, technology and manufacturing must be realized and tested before starting the PHEV mass production.

6. Efficiency

The liquid hydrocarbons are optimal for transport due their extremely high energy density when in 50kg tank can be stored 500kWh, it is of course the thermal energy, but if the total efficiency (of all the energy conversion from fuel to heat, mechanical force on piston, torque from crankshaft, via gearbox and axis to the wheels) is only 16 - 24%, as is calculated in Table 6. Taking the middle value 20% there is the traction energy 100kWh to disposal. The common passenger car with such petrol can run between 500 and 1000km. It is about 0,2kWh/km and for 60km must be in the battery more than 12kWh.
In the Table 6 is the survey of all components of drive train with typical efficiencies and for more vehicles and operating modes is the total efficiency calculated. From first two rows is evident, that the classical petrol car in city transport has 50% increased fuel consumption, because its engine works with lower efficiency at low power (Fig.11). The new symbols in Table 6 are MGB for manual gearbox, REC for AC/DC inverter (rectifier), INV for DC/AC inverter and RDG for reduction and differential gearbox.
The PHEV without ICE has efficiency 77% if calculated from the battery energy, but only 54% if calculated from the plug. If the PHEV charges its battery from running ICE, its total efficiency can fall under the classic vehicle in the city traffic and if its ICE will be used only for EM supply its efficiency is still under the classic vehicle. Last example in the table is for Diesel – electric drive on big locomotive (Fig.9), where due better efficiencies of big power components is also the total efficiency satisfactory.

	ICE	GEN	MGB	REC	BAT	INV	EM	RDG	TOTAL
Classic Car	0,30	---	0,85	1,00	---	---	---	0,95	**0,24**
Classic Car - City	0,20	---	0,85	1,00	---	---	---	0,95	**0,16**
PHEV - Electric						0,95	0,85	0,95	**0,77**
PHEV - Electric					0,70	0,95	0,85	0,95	**0,54**
PHEV – Charging BAT	0,30	0,85	---	0,95	0,70	0,95	0,85	0,95	**0,13**
PHEV – No Charging	0,30	0,85	---	0,95	1,00	0,95	0,85	0,95	**0,19**
Loco D-E - 1MW	0,38	0,90	---	0,95	1,00	0,95	0,90	0,95	**0,26**

Table 8. Efficiency of Drive Train for Various Vehicles

6.1 Diesel-electric transmission

Diesel electric transmission is effectively used in locomotives for rail transport, but there is no energy accumulator in the power train and the generator – inverter – motor (Fig.9) works here as an alternative to mechanical shafts and gearboxes, with better flexibility and high efficiency. It is also the rated power of components, which gives the nice efficiency, because the motors are in the power 100 – 1000kW. The greater rated power the higher efficiency is standard property of every machine.

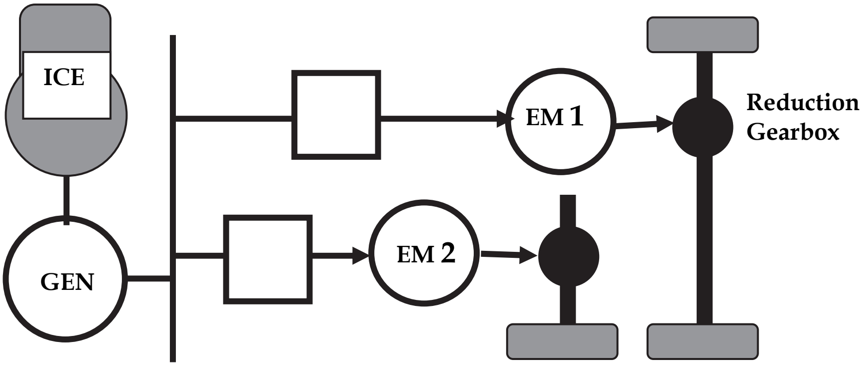

Fig. 9. Typical configuration of Diesel – Electric Locomotive (serial power flow)

If the PHEV would be, after spending the energy accumulated in battery from the grid, operated similar way as this diesel – electric loco without charging the battery from engine and the battery would be used only in the same mode as is in actual HEV, that means for accumulating of kinetic energy during recuperative braking, the electric power train efficiency has not be so bad.

From this locomotive can be also copied the multi-motor scheme when each axis has one EM. For road vehicle it can be the advantage if any wheel has its motor, but small motors are again less efficient. Possible solution can be the drive management with switching-off the motors at constant speed, when the individual EM for each wheel allows the optimal regenerative braking with ABS control, preventing the wheel blocking, because every wheel torque and speed can be controlled separately. The storage system can return the energy from braking into next acceleration and reduce the energy consumption, but it is similar as in standard hybrid, when greater battery capacity allows to store not only the energy from one acceleration - deceleration cycle, but also (in mountainous countries) to exploit the potential energy from downhill drive for next uphill climb.

6.2 HEV efficiency

What is the fuel savings composition in HEV is briefly explained in Fig.10, where the negative influence of increased vehicle mass (battery + EM) represents the first column. The next three columns are contributions from HEV technology given by no ICE idle run, ICE speed control and EE recuperation by electric braking.

The standard HEV as is in Fig.1 saves the fuel only in the city traffic. The ICE specific fuel consumption is in Fig.11 and it is evident, that for the torque under 15% of rated value, the fuel consumption grows more than twice.

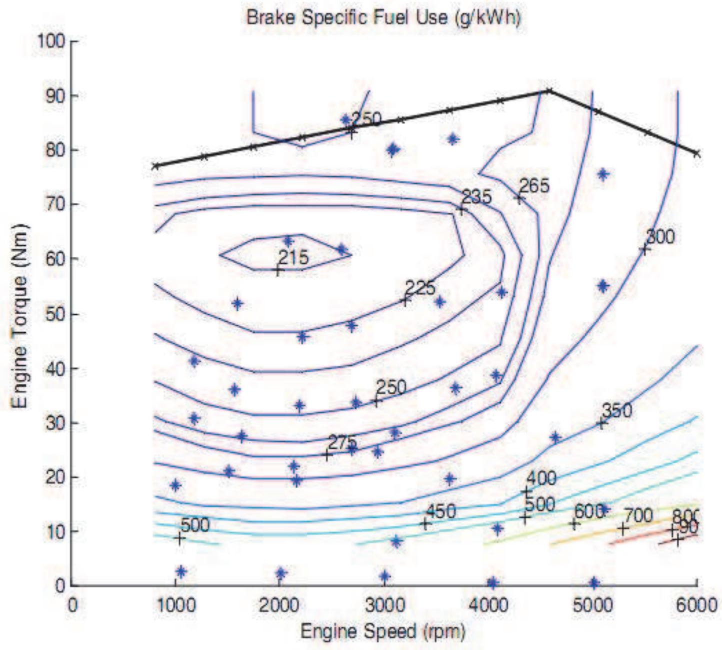

Fig. 11. Specific Fuel Use for ICE in Honda Insight

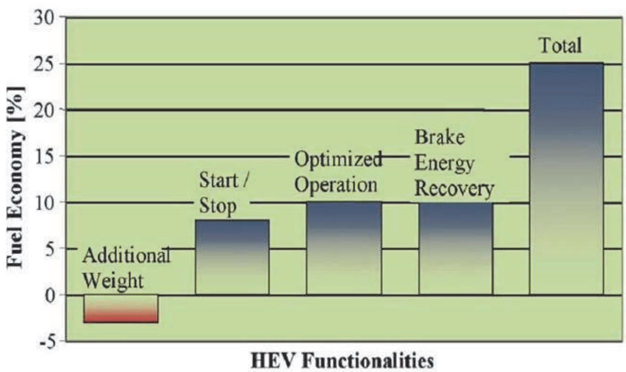

Fig. 10. Fuel saving components of HEV in city transport

7. Options

The serial PHEV is also good alternative for military vehicles and other vehicles for operation out of civilization and out of grid, where the battery can be charged only from Diesel-generator. Here is not the advantage of night charging from the plug, but the generator with battery can serve as an independent power source for local DC or AC grid from inverter. So it can be said, that such vehicle is more plug-out than plug-in, but its composition is similar, maybe with higher ICE and generator power.

7.1 PHEV without generator

The last time concepts of PHEV suppose also solutions with mechanical connection of ICE to wheels in highway traffic mode, when the EM and generator can be smaller and thanks "shorter" drive chain the fuel consumption can be reduced comparing with electric chain. Such concept can separate also the wheels driven by ICE and by EM and the typical front-wheel drive vehicle can be can be equipped with electric rear-wheel drive.

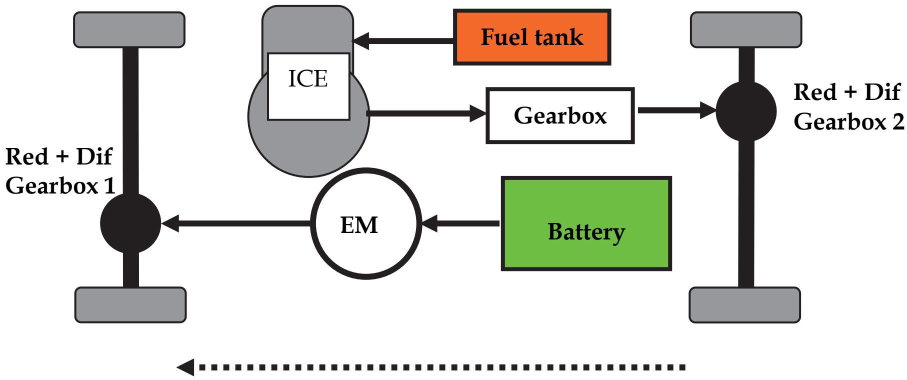

Fig. 12. PHEV without Generator

Because the charging from ICE is not very efficient and does not save the fuel, it is possible to realize the vehicle, where each axis is driven by one motor (Fig.12). For short distance trips the axis 1 is driven by EM supplied from battery and here can be also the energy recuperated from braking or downhill rides. For the long distance trips on highways the ICE drives the axis 2, which is connected to the first axis only by road surface, EM does not help in drive, but it can again recuperate and in low speed drive, when the ICE does not work with high enough efficiency, the driving torque from ICE can be bigger than is necessary and EM can in generator run the surplus energy change into EE and charge the battery. Instead of generator in Fig.3 here is the gearbox (manual or automatic) and the second reduction and differential gearbox, both are from standard production. It is perfect union of two independent drives available in emergency.

8. Conclusions

The reasons for PHEV are

- Ecology, because the energy from renewable power sources reduces the carbon emissions
- Independence on oil import, because practically all suitable fuels for the ICE are produced from oil. Coal hydrogenation was also developed in the war years and in some tropical countries (like Brasilia) there are produced the alcohol fuels from plants

with sugar. For Diesel engines there is produced the oil from plants in the last years, to replace the mineral oils.

- Efficiency, especially in the city transport with low average speed and often stops and traffic jam, where the combustion engine works with very low efficiency and also much of fuel is spent in idle run.
- Safety, due more automatic drive control in electric transmission drive train

The greatest advantage of the PHEV mass production is important oil consumption decrease and increase of electricity production in the night hours when the price is minimal. The distributors are also planning the smart grids in near future based on numerous batteries in PHEV (or battery only vehicles) which can help to control the electrical energy balance in grid for keeping the high quality parameters without voltage dips and sags.

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10. References

Heršlica, V. (2008) Super-capacitor integration into hybrid vehicle power source, In *Proceeding of International Conference on Renewable Energies and Power Quality (ICREPQ'08),* pp. 6, ISBN 978-84-611-9290-8, Santander, Spain

Bršlica, V. (Sept. 2005), Co-generative Power Source for Electric Car, *Proceeding of VPPC 2005,* IEEE Cat. No.: 05EX1117C, (CD-ROM) ISBN 0-7803-9281-7, Chicago IL USA

Altairnano, NanoSafe Battery Technology, ALTI 070404, pp. 4, In web *Altairnano.com*

Buchmann, I., How to prolong lithium-based batteries, BatteryUniversity.Com http://www.batteryuniversity.com/

Stober, D. (2007), Nanowire battery can hold 10 times the charge of existing lithium-ion battery, *Stanford News service*,

Fehrenbacher, K. (2009), Reva to Boost Range with Lithium-Ion Battery, *Earth2tech*, http://earth2tech.com/2009/01/05/

Total Lithium-Ion Battery Sales Forecast to Double By 2012 to US$13.1B In *Green car congress*, http://www.greencarcongress.com/ 28.11.2008

Candace, K. et al., (2007), High-performance lithium battery anodes using silicon nanowires, *Nature Nanotechnology* 3, 31 – 35 pp., December 16, 2007,

Soinoff, N. Lithium Battery Power Delivers Electric Vehicles to Market, *Scientific & Technical Information*, http://www.sti.nasa.gov/tto/Spinoff2008/t_1.html

Deguzman, D. (2009), The race for car lithium battery is on, *Green Chemicals*, http://www.icis.com/blogs/green-chemicals/ January 7, 2009

Miller, C. (2008), Electric-Car Battery Makers Seek Federal Funds, December 26, 2008, http://bits.blogs.nytimes.com/2008/12/26/electric-car-battery-makers-seek-federal-funds/

Parker, R. (April 2009), Chevy Volt Battery Over-engineered Due To Unknowns, http://www.futurepundit.com/archives/cat_energy_batteries.html

Byoungwoo Kang & Gerbrand Ceder, Battery materials for ultrafast charging and discharging, *Nature 458*, pp. 190-193, March 12, 2009

Weir, R. D. et al., (2008), Utilization of poly(ethylene terephthalate) plastic and composition-modified barium titanate powders in a matrix that allows polarization and the use of integrated-circuit technologies for the production of lightweight ultrahigh electrical energy storage units (EESU), *United States Patent 7,466,536*, December 16, 2008

Weir, R. D. et al., (2006) Electrical-energy-storage unit (EESU) utilizing ceramic and integrated circuit technologies for replacement of electrochemical batteries, *United States Patent 7,033,406*, April 25, 2006

Ehrenber, G., Scott G. et al., (2008), Nanoparticle ultracapacitor, *United States Patent Application 20080316678 Kind Code A1*, December 25, 2008

Ilyanok, M. A. (2007), Quantum Supercapacitor," United States Patent 7,193,261 B2, March 20, 2007

Eisenring, R. (2008), Method of storing electricity in quantum batteries, *United States Patent Application 20080016681 Kind Code A1*, January 24, 2008

2009 Tesla Roadster Technical Specifications, http://www.teslamotors.com/performance/tech_specs.php

Chevy Volt: Reasons for Use and Cost of Operation http://gm-volt.com/chevy-volt-reasons-for-use-and-cost-of-operation/ EEStore Energy storage unit, http://bariumtitanate.blogspot.com/http://www.toyota.com/prius/ http://automobiles.honda.com/civic-hybrid/ http://www.chevrolet.com/electriccar/http://www.gm-volt.com/ http://www.ecom.cz/katalog_pdf/maxwell.pdf

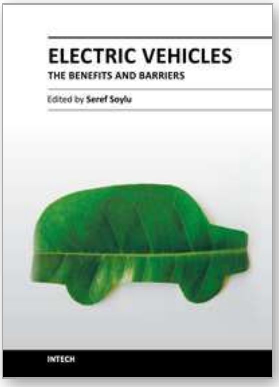
Hund, T. (2004) Comparison Testing of Supercaps, Sandia National Laboratories, Albuquerque, NM, November 2004

United States Patent 7 033 406, http://www.freepatentsonline.com/7033406.html http://www.toshiba.co.jp/about/press/2007_12/1102/SCiB.pdf

Schindall, J. (2007), The Charge of the Ultra - Capacitors (Nanotechnology takes energy storage beyond batteries) http://www.spectrum.ieee.org/nov07/5636

Lockheed Martin Signs Agreement with EEStor, Inc. for Energy Storage Solutions, 10th January 2008, http://www.gm-volt.com/2008/01/10/lockheed-martin-signs-agreement-with-eestor/

Edgar, J. Brake Specific Fuel Consumption http://autospeed.com/cms/title_Brake-Specific-Fuel-Consumption/A_110216/article.html http://en.wikipedia.org/wiki/Brake_specific_fuel_consumption



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In this book, theoretical basis and design guidelines for electric vehicles have been emphasized chapter by chapter with valuable contribution of many researchers who work on both technical and regulatory sides of the field. Multidisciplinary research results from electrical engineering, chemical engineering and mechanical engineering were examined and merged together to make this book a guide for industry, academia and policy maker.

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