1 Overview of Battery Technology for HEV

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1.1 Abstract

Several electric energy storage systems exist with different principles and characteristics. On the other hand, there are also various hybrid electric vehicles with specific requirements. This paper gives an overview of the advantages/disadvantages and practical aspects of battery technologies and ultracapacitors which can be used in hybrid electric vehicle applications. The summary is limited to only likely candidates. This text is not aimed at specialists of battery technology, but should be conceived as an introduction to this topic.

1.2 Introduction

This chapter deals with electric energy storage systems, batteries and ultracapacitors, for hybrid vehicles. Other storage systems like flywheels and hydraulic vessels are not considered, because these systems have not proven to meet the requirements without incurring unacceptable disadvantages.

Different technologies for electric energy storage exist today. Only the most suitable for hybrid electric vehicles will be dealt with in detail. As such the following types are being considered:

- lead acid batteries;
- alkaline or nickel based batteries like NiMH;
- lithium based batteries;
- ultracapacitors;
- others like Zebra and Zn-air batteries.

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[1] The International Energy Agency (IEA), based in Paris, is an autonomous agency linked with the Organization for Economic Co-operation and Development (OECD). The IEA is the energy forum for 26 Member countries. IEA Member governments are committed to taking joint measures to meet oil supply emergencies. They have also agreed to share energy information, to co-ordinate their energy policies and to co-operate in the development of rational energy programmes.

Annex VII "Hybrid Vehicles" is part of an IEA "Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes". This Agreement is an international collaboration programme in which currently 8 countries participating in six Annexes, that each deal with different aspects related to electric, fuel cell and hybrid vehicles. The participating countries in the Hybrid and Electric Vehicle Implementing Agreement are: Austria; Belgium; France; Italy; The Netherlands; Sweden; Switzerland; United States.

Several aspects of each technology will be dealt with. The ideal energy storage system is small but delivers high power and contains much energy. It does all this at low cost and as long as the vehicle lasts. Today, the situation is not ideal. Therefore this study looks into different characteristics of energy storage systems that are important for HEV applications:

- energy density;
- power density;
- maximum allowed currents for charge/discharge;
- life performances: calendar-life and cycle life;
- thermal requirements;
- abuse and endurance performances;
- safety and monitoring issues;
- costs.

The current market situation is very interesting. Hybrid electric passenger cars are being introduced in the market. They are still a niche product, but the number of available models as well as the yearly production of each model increase. Electric energy storage is also at a crossroad where the technology choice may shift from NiMH to Li-based.

1.3 Electric Energy Storage Technologies

1.3.1 Lead Acid Battery Technology

The lead acid battery is based on the chemical reactions between lead, lead oxide and sulphuric acid (electrolyte). When the battery delivers power the following reactions take place:

$$\begin{array}{lrcl} Anode & PbO_2+H_2SO_4+2H^+ +2e^- & \Rightarrow & PbSO_4+2H_2O \\ Cathode & Pb+SO_4^{--} & \Rightarrow & PbSO_4+2e^- \\ Overall & PbO_2+H_2SO_4+Pb & \Rightarrow & 2PbSO_4+2H_2O \end{array}$$

During the discharge process sulphuric acid is converted to lead sulphate. During the charging process the reactions are reversed. Due to the exchange of ions between the electrodes and the electrolyte there is a potential difference resulting in the cell voltage. The cell voltage depends on the concentration of sulphuric acid in the electrolyte. This concentration decreases during discharge resulting in a lowering cell voltage.

During charging, especially overcharging, a part of the electrolyte separates into oxygen and hydrogen. A solution is the use of sealed, valve regulated PbAc (VRLA) batteries that are designed to retain and recombine these gases. By using an electrolyte design that reduces gassing and a catalyst that causes the hydrogen and oxygen to recombine into water, also called a recombinant system, the electrolyte is kept in good condition over a longer time.

The popularity of lead acid batteries in general and the reason why they have been used in some vehicle applications is based upon some good characteristics. It is a proven technology available at a low cost. Moreover, they can withstand high currents. But a major component in these batteries is lead. Consequently, battery weight is high. This results in low power and energy densities. Moreover, at the end of life these batteries require the correct recycling methods to reduce its environmental burden.

1.3.2 Alkaline batteries

These batteries have their name derived from the applied alkaline electrolyte. Alkaline batteries use nickel oxide as cathode material. For anode material several options exist. In this text only metal hydride (NiMH batteries) will be dealt with. NiCd and NiZn batteries are not well suited for HEV applications for various reasons.

NiMH batteries

NiMH batteries use a different chemistry at the anode. Instead of cadmium or zinc, hydrogen is used as the active element at the anode. This electrode is made from a metal hydride, hence the naming of this battery type.

$$\begin{array}{lrcl} \text{Anode} & NiOOH+H_2O+e^- & \Rightarrow & Ni(OH)_2+OH^- \\ \text{Cathode} & MH+2OH^- & \Rightarrow & M+H_2O+e^- \\ \text{Overall} & NiOOH+MH & \Rightarrow & 2Ni(OH)_2+M \end{array}$$

Like NiCd batteries, typical cell voltages are 1.2 V, but NiMH batteries offer advantages over NiCd batteries resulting in a phasing out of the latter, namely:

- higher energy density;
- less memory effect;
- environmentally friendly (no cadmium, mercury or lead);
- robust, i.e. more tolerant for over charge and over discharge conditions and this allows a simpler battery management.

NiMH batteries are the first batteries to be used on a large scale in HEVs. Over 200 000 Toyota Prius cars have been equipped with this battery technology.

NiMH batteries are also widely used for consumer products where they can replace primary 1.5 V batteries. The smaller memory effect as well as their large capacity[2] make them the first choice.

But NiMH batteries have some drawbacks too. Compared to other battery technologies they have a high self discharge rate. Furthermore, the coulombic efficiency of NiMH batteries is lower compared to NiCd and PbAc batteries. This results in a lower efficiency of the charge/discharge cycle.

1.3.3 Lithium based batteries

Battery technology is based on the use of metals. The technologies described above use the very heavy lead (density 11 340 kg/m³) and the rather heavy nickel (density 8 800 kg/m³). In the search for lighter batteries, providing higher energy and power densities,

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[2] Some manufacturers of digital cameras recommend the use of high capacity NiMH batteries above primary alkaline batteries because their capacity is larger. Consequently, the NiMH batteries allow to take more pictures with one charge than the primary batteries can.

lithium (Li, density 530 kg/m³) is the ultimate metal[3]. Although this metal may be somewhat unknown, it is abundantly available like Ni, Zn or Pb in the upper earth crust.

Next to its low density, Li has the highest electrochemical potential. This results in a high single cell voltage from 2 to 5 V depending on the chosen chemistry. This higher voltage also helps to achieve very high energy and power densities that are important in EV and HEV applications.

Like with alkaline and nickel based batteries, lithium based batteries comprise several chemistries. The most common are Lithium-ion (LiIon) and Lithium-Ion Polymer or in short Li Polymer. Some other Lithium chemistry variants are mentioned with their major benefits and drawbacks.

Note that lithium based batteries always have the risk of fumes or flames in case of deep over charge (about 200 %).

LiIon

LiIon is the most common variant of Li-based rechargeable batteries. Carbon is used for the anode and lithium cobalt dioxide ($LiCoO_2$) is taken for the cathode. Lithium ion secondary cell chemistry depends on an "intercalation" mechanism . This involves the insertion of lithium ions into the crystalline lattice of the host electrode without changing its crystal structure, see figure 1. These electrodes have two key properties:

- open crystal structures which allow the insertion or extraction of lithium ions;
- the ability to accept compensating electrons at the same time.

Because lithium reacts violently with water, the electrolyte is composed of non aqueous organic lithium salts and acts purely as a conducting medium and does not take part in the chemical action. Due to the absence of water in the chemical reaction, the formation of hydrogen and oxygen gases (outgassing of the electrolyte) is also eliminated.

The cell chemistry and electrodes allow the use of very thin separators. This permits the electrodes to have high surface areas. Consequently LiIon batteries are able to handle high currents.

LiIon cells provide 3.6 V. So each cell is the equivalent of three NiCd or NiMH cells with the same capacity. This makes battery packs less complex. Energy density is also better. Hence LiIon cells have replaced other chemistries in portable applications like mobile phones, laptops and consumer electronics.

High discharge rates up to 40 C as well as deep cycling are possible. Cells maintain their voltage up to a DOD of 80 %. This benefit is also a drawback when trying to derive the SOC of such cells.

Fast charge is possible but the batteries are sensitive to overcharging. Overcharging may cause loss of capacity. Therefore the use of protective circuitry is required. Compared to the other chemistries, charging is based on constant current followed by constant voltage charging. Trickle charging is not allowed. Due to the sensitivity for overcharging, partial charges are beneficiary.

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[3] The choice of the metal in a battery is not the only factor determining the battery mass. Hence PbAc batteries will not be 21 times heavier for the same capacity, power or energy content.

LiIon cells have no memory effect.

The experience in low power applications does not allow to predict the battery behavior in high power applications like HEVs. However accelerated life tests indicate that for these applications the same life can be expected.

LiPolymer

Lithium polymer cells are a special version of the LiIon cells. The free electrolyte is replaced by an electrolyte in a matrix of an ion conductive polymer. This solid electrolyte is safe and leak resistant. Hence packaging the cells is simplified and allows a lot more shapes.

LiPolymer batteries are less sensitive for overcharge, abuse and damage than LiIon cells. The thicker electrolyte separator results in a higher energy density but a lower current density. So, LiPolymer batteries are better suited for high capacity, lower power applications compared to LiIon batteries.

Other lithium chemistries

The other lithium chemistries are either not commercially available yet or show drawbacks that prevent their wide commercialization. Some are listed below.

Lithium manganese

The lithium manganese ($LiMn_2O_4$) combines a higher cell voltage (3.8 to 4 V) with a lower energy density compared to LiIon. Lithium manganese is safer and more environment friendly than lithium cobalt dioxide.

Lithium nickel

Lithium nickel ($LiNiO_2$) has a higher energy density, but a lower cell voltage (3.6 V). The chemistry develops heat. So thermal management of battery packs will be required.

Lithium phosphate

In lithium phosphate cells the cathode is made of lithiated transition metal phosphates. The use of these cathodes provides better thermal and chemical stability. This increased stability makes these cells safer.

The choice of the transition metal in the cathode allows to obtain cell voltages between 2.1 and 5 V. Compared to the cobalt chemistry, lithium phosphate offers lower cost, higher safety and better environmental characteristics. One drawback is the lower energy density.

1.3.4 Ultracapacitors

Ultracapacitors offer another technology to store electric energy. The technology is based on physical processes (electrostatic charging) - instead of electrochemical processes cf. batteries - resulting in characteristics that are different from batteries.

Electric capacitors store energy by separating two opposite charges, thus by creating an electric field. This energy is stored in a very thin layer, a dielectricum. The capacity is proportional to the surface area of the electrode and opposite proportional to the thickness of the dielectricum.

Ultracapacitors follow the same basic concept, but their capacity is several orders of magnitude higher (F to kF vs. pF to mF). When a voltage is applied on the electrodes, the ions of the electrolyte move to the electrode of the opposite charge under influence of the electric field, see figure 2. The charges are thus located at the contact between electrode and electrolyte, i.e. in the pores of the electrolyte. An ion-layer is formed both on the positive as on the negative electrode, creating a dielectricum. As a result, two capacitors in series are created. Therefore, ultracapacitors are also referred to as “double layer capacitors”. Note that the materials of the positive and negative electrode can be the same (activated carbon), “symmetric design”, or different (activated carbon and a metal hydroxide), “asymmetric design”. The capacity of the ultracapacitor depends on the material of the electrode and the electrolyte.

The high energy content of ultracapacitors in comparison to aluminum electrolytic capacitors originates in the activated carbon electrode material which has an extremely high specific surface area of about 2000 m^2/g, caused by many, minuscule pores, and the extremely short distance between the opposite charges of the capacitors which is of the order of a few nanometers (2 à 5 nm).

The very thin electrodes and electrolyte allow to make cylindrical ultracapacitors by winding the layers in a spiral. This is depicted below, figure 3. Powder technology can be wound into round shaped capacitors, leading to faster process flow techniques. It is common practice to soak the separator (paper, polymer membranes or glass fibers) in a highly conductive organic electrolyte to establish ion movement during charge and discharge cycles. An organic electrolyte has the advantage that the voltage over a single cell can attain relatively high values prior to electrolyze of the electrolyte occurs. The maximum voltage of ultracapacitors has increased to 2.5 V. Higher voltages will reduce the lifetime considerably.

When an ultracapacitor is charged or discharged at a constant current, the voltage will increase, respectively decrease linearly. Discharge down to 0 V is possible, but up to 0.5 times the maximal voltage is used in real applications. In this case, 75 % of the energy is delivered.

The technology is rather new and mainly produced by 4 companies worldwide[4]. Ultracapacitor advantages and disadvantages, compared to batteries, are:

+ the charge/discharge cycle is very efficient (95%)
+ can accept and deliver large currents
+ long lifetime (>100 000 cycles) due to physical instead of electrochemical processes
+ low weight (compared to some battery technologies)
+ easier to define SOC: voltage changes with SOC (energy content $E = \frac{1}{2} C \cdot U^2$)
+ faster dynamic response to the load profile due to physical instead of electrochemical processes
+ charged and discharged with the same power for a temperature range of -30 to 70 °C (this results in limited energy losses during regenerative braking)
- larger volume

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[4] These manufacturers are: Epcos (www.epcos.com), Maxwell Technologies (www.maxwell.com), Nesscap (www.nesscap.com) and Esma-Cap (www.esma-cap.com).

- voltage changes with SOC, requiring more complicated drive electronics
- over-charging damages ultracapacitors
- limitation of energy content

The high charge/discharge cycle efficiency can somehow be counteracted by the driver electronics that needs to operate with voltages varying more than with batteries. This will cause higher conversion losses.

As the maximal voltage of a single ultracapacitor is only 2.5 V, several ultracapacitors have to be connected in series to a module if higher supplying voltages are required. Furthermore, caused by different self-discharge of the single ultracapacitors, the individual voltages of the module will drift away. Finally, the ultracapacitor module will be mismatched in voltage. Battery systems will be usually overcharged to keep it balanced in charge and voltage. However, ultracapacitors can not be overcharged; degradation occurs during operation in consequence of overcharging. Therefore, special charge-balancing systems must be incorporated. These charge-balancing systems exchange the energy between the single ultracapacitors in such a manner, that all ultracapacitors achieve equal voltages.

Ultracapacitors have characteristics complementary to those of batteries. Where batteries, due to their internal resistance, react to current changes with voltage changes, ultracapacitors have a gradual change of voltage. Since in general, ultracapacitors have lower impedances than batteries, these ultracapacitors will provide the higher currents while the batteries absorb/supply additional low level currents from/to the ultracapacitors to correct for voltage inequalities [1]. Consequently, with the same current exchange cycle, the battery combined with ultracapacitor will operate in a narrower voltage margin. This narrower battery cycling range has the potential to increase battery life and is illustrated in figure 4.

Additionally, the combination of both technologies offer both high power capability (ultracapacitors) and adequate energy storage (batteries). This hybrid battery[i], may well be the outcome for hybrid vehicles. But there is still some work needed to reduce the large volume, mass and cost of this combined energy storage and to improve the hybrid energy controller so the mileage and performance are optimized. Furthermore, if both technologies are not directly coupled, there is a need to have DC/DC converters between the ultracapacitors and motor adding even more cost.

1.3.5 Other energy storage technologies for HEV

ZEBRA-batteries

ZEBRA-batteries use a different chemistry (sodium sulphur) and need to be operated at elevated temperatures (300°C). The high operation temperatures limit ZEBRA-batteries to larger vehicles that are almost continuously in operation. Performance levels are similar to NiMH-batteries.

The ZEBRA batteries are not included in the above comparison as they are not mentioned in most literature. Furthermore, no recent developments have been announced since 1999, indicating that their development has come to a halt.

Zinc air

Zinc air batteries combine high energy density with high power. Furthermore it is made of inexpensive materials. But the batteries are sensitive to extreme temperature and humid conditions. Once activated the electrolyte tend to dry out and the batteries have to be used quickly.

High power batteries such as those designed for EVs and HEVs can use mechanical charging in which discharged zinc cartridges are replaced by fresh zinc cartridges. The used cartridges are subsequently recycled.

1.3.6 Wear

Battery ageing illustrates performance deterioration during cycling or storage. Concerning vehicle use and battery cycling, the main ageing modes are [2]:

1) for aqueous electrolyte type batteries (amongst others PbAc and NiMH):

- current collector corrosion due to end of charge or floating current; this ageing mode, highly dependent on temperature, will be responsible for an internal resistance increase; in case of large corrosion the corresponding failure mode could be a collector rupture causing an abrupt failure;
- deterioration and loss of positive electrode active material during cycling, this ageing mode will have as a consequence a decrease in element capacity;
- electrolyte loss due to water electrolyte electrolysis, principally encountered in recharge phases carried out at a too high voltage (above oxygen generation threshold); this ageing mode will be responsible for an increase in internal resistance.

2) for non aqueous electrolyte type batteries (amongst others LiIon):

- lithium oxidation by the electrolyte;
- deterioration and loss of active material on the positive electrode during cycling;
- other ageing modes may be encountered, such as disequilibrium in negative electrode state of charge.

As a consequence of these factors, battery ageing will generally be expressed through two modes:

- decrease in capacity due to deterioration and loss of active material on the positive electrode;
- decrease in peak power capabilities (charge and discharge) due to internal resistance increase.

Since the technology of ultracapacitors is based on physical processes, their wear is very limited in comparison to the wear of batteries.

1.4 Comparison of Electric Energy Storage Technology

In this section a selected number of battery technologies will be compared with respect to their characteristics and specifications that are relevant in vehicle applications. The technologies that will be considered are:

- lead acid due to its application in many heavy duty hybrid vehicles up to today;
- NiMH as the choice of passenger car OEMs;

- LiIon as a very promising battery technology;
- Ultracapacitors as a possible valuable alternative for batteries.

Overview of the characteristics of several energy storage technologies

For in-vehicle applications the following characteristics are important:

Cell voltage: determines the number of elements that have to be connected in series to obtain the required supplying voltage.

Specific energy, energy density, specific power and energy power. Both the specific energy expressed in Wh/kg (weight) as the energy density inWh/dm³ (volume) are important. To achieve higher fuel economy, low total vehicle mass is mandatory. Adding several hundreds of kilograms of batteries will not be beneficiary to achieve better efficiencies from hybridization. Also the compactness of the batteries is important. Manufacturers try to offer a maximum internal volume to the vehicle users with minimum external size. Batteries have to fit into spaces that are small and will most probably not be used in the conventional version of the vehicle.

In a similar way battery packs have to be small and light while providing high power output and accepting high power input.

Number of deep cycles: the total number of full charge/discharge cycles over the life time of the energy storage system. So, taking into account the energy management system which determines the DOD, this value gives an idea of the durability (and thus also costs and drive-ability) of the system.

Self discharge: the electrical capacity that is lost when the cell is not in use.

Table 1 gives an overview of some of the most important characteristics of battery technologies. Note that most parameters are dependent on temperature, SOC and time frame [3 and 4]. Thus so, these are indicative values, also determined by the technological progress and the manufacturer.

Energy storage requirements of hybrid configurations

Table 2 gives an overview of the energy storage requirements for several HEV configurations [5].

Comparison of energy storage technologies for HEVs

PbAc technology offers good power density and available discharge power, but has quite low specific energy and specific power. Therefore their use is not recommended for applications which demand a large amount of power and energy, as power-assist HEVs. On the other hand, these characteristics make PbAc batteries well suited for soft/mild hybrid applications. Note that the characteristics and requirements vary between passenger car and heavy duty HEVs, for example, the relative weight of a battery pack will be substantially different. Additionally, the maturity of the PbAc technology makes it cost-efficient and also suitable for heavy duty applications.

NiMH batteries deliver good energy throughput, are high rechargeable and a proven design in high power applications [6]. This technology is thus well suited for power-assist/full hybrid applications. Important disadvantages are the high self discharge and the need for thermal management systems.

LiIon is a very promising battery technology for HEV applications. The low weight and efficient chemistry result in high specific energy/power and energy/power density. LiIon has the additional benefits of having a higher cell voltage and capable of storing more energy compared to NiMH. The LiIon technology has high potential for next full HEVs, but it has to been taken into account that LiIon batteries are sensitive to over charge and consequently, a battery management system is required.

Ultracapacitor applications are most likely in HEVs with start-stop strategies (need for low temperature power capability and low energy). This provides the biggest opportunity if engine shutdown becomes a regulation/mandate during idles. With mild hybridization, the ultracapacitor energy is sized well for frequent regenerative braking, but for heavy hybridization, the acceleration requirement (peak power condition) requires greatly over sizing ultracapacitor energy and thus results in an impractically large mass and volume of the ultracapacitor [7]. Concluding, hybridization with ultracapacitors can provide benefit, but ICE/fuel cell downsizing is limited.

The combination of ultracapacitors and batteries may have some applications in mild HEVs, even in full HEVs, but added cost and volume could be an issue.

Regenerative braking

Electrical motors have the interesting possibility to work both as a motor and as a generator. In this way, not only electrical energy can be converted to mechanical energy, but also the other way around. Thus, when the motor acts as a generator, kinetic energy will be converted in electrical energy. This is an interesting possibility to regain the vehicle’s energy and called regenerative braking.

When a vehicle brakes firmly, there is a lot of kinetic energy that can be converted into electrical energy, but this energy is only available for a few seconds. Batteries have the disadvantage that they can not be charged fast, so only a small amount of the kinetic energy will be stored and the remainder will cause the batteries to heat up. This is the reason that regenerative braking is not very efficient if there are only batteries to store the energy. Ultracapacitors on the other hand, do have the capability to store a lot of energy in a short time. Their functioning does not rely on (slow) chemical reactions and thus so, are better suited for the job.

Battery management system

Series connected battery packs in EVs and HEVs require monitoring equipment that is capable of measuring the voltages of individual segments (several modules/cells connected in series) to prevent damage and identify defective segments [8]. Virtually all types of batteries can be damaged by excessively high or low voltages and in some cases the results can be catastrophic. Therefore, once high or low voltage segments have been identified, some equalization process also must be used to re-balance the voltages. Imbalances are especially prevalent in EVs and HEVs since the batteries are frequently charged and discharged.

Since the safety of the battery pack is dependent on the management system, the reliability of the management system becomes very critical. Therefore, various hardware and software safety features are required to secure the battery pack in case of malfunction. It is also very important to control the cost when adding additional features and enhancing existing functions. In addition, the size and weight need to be minimized to allow the BMS to fit into compact battery packs.

Battery thermal management

Battery performance, life and cost directly affect the performance, life and cost of the EVs and HEVs. Battery temperature influences the availability of discharge power (for start up and acceleration), energy and charge acceptance during energy recovery from regenerative braking. These affect vehicle drive-ability and fuel economy. Temperature also affects the life of the battery. Therefore, ideally batteries should operate within a temperature range that is optimum for performance and life [9] and depends on the electrochemistry. Usually, the optimum temperature range for the battery operation (desired by the battery manufacturer) is much narrower than the specified operating range for the vehicle (identified by the vehicle manufacturer).

In addition to considering the (absolute) temperature of a battery pack, uneven temperature distribution in a pack should be also considered. Temperature variation from module to module in a pack could lead to different charge/discharge behavior for each module. This, in turn, could lead to electrically unbalanced modules/packs and reduced pack performance.

The goal of a thermal management system is to deliver a battery pack at an optimum average temperature with even temperature distribution. However, the pack thermal management system has to meet the requirements of the vehicle as specified by the vehicle manufacturer; it must be compact, lightweight, low cost, easily packaged and compatible with location in the vehicle. It must also use low parasitic power, allow the pack to operate under a wide range of climate conditions and provide ventilation if the battery generates potentially hazardous gases.

1.5 Conclusion

The energy storage technologies that are relevant in hybrid electric vehicle applications, are lead acid, used in many heavy duty hybrid electric vehicles up to today and suited for soft/mild hybrid applications. NiMH is the current choice of passenger car OEMs for power assist/full hybrid applications. LiIon is a very promising battery technology, mainly for full hybrid applications. Ultracapacitors are a possible valuable alternative for batteries for soft/mild hybrid applications. The combination of ultracapacitors and batteries may have some applications in mild HEVs, even in full HEVs, but further development is needed. Dependent on the electric energy storage system there might be a requisite to implement battery management and/or thermal management systems.

References

1. M. D. Zolot; B. Kramer, *"Hybrid Energy Storage Studies Using Batteries and Ultracapacitors for Advanced Vehicles"*, 12th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Deerfield Beach, Florida, December 2002.

2. F. Badin, O. Briat, S. Olivier, B. Jeanneret, R. Trugui, B. Malaquin, *“The use of batteries in hybrid vehicles”*, Symposium IEEE VTS – Vehicle Power and Propulsion, Paris, October 2004.

3. INVESTIRE-network, *“Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and Recommended R&D Strategy”*, funded by the European Community under the 5th Framework Program, 2002.

4. A. Pesaran, M. Zolot, T. Markel, K. Wipke, *“Fuel Cell/Battery Hybrids: An Overview of Energy Storage Hybridization in Fuel Cell Vehicles”*, 9th Ulm Electrochemical Talks, Germany, May 2004.

5. A. Pesaran, T. Markel, M. Zolot, S. Sprik, *“Ultracapacitors and Batteries in Hybrid Vehicles”*, Advanced Capacitors, San Diego, California, July 2005.

6. C. Rosenkranz, *“Deep Cycle Batteries for Plug-in Hybrid Application”*, EPRI Workshop at EVS 20, November 2003.

7. M. Zolot, T. Markel, K. Wipke, A. Pesaran, *“Potential Ultracapacitor Roles for Hybrid Electric Vehicles”*, 13th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Deerfield Beach, Florida, December 2003.

8. T. Stuart, F. Fang, X. Wang, C. Ashtiani, A. Pesaran, *“A Modular Battery Management System for HEVs”*, University of Toledo, U.S. Department of Energy, DaimlerChrysler, National Renewable Energy Laboratory, 2002.

9. A. Pesaran, *“Battery Thermal Management in EVs and HEVs: Issues and Solutions”*, Advanced Automotive Battery Conference, Las Vegas, Nevada, February 2001.

Tables

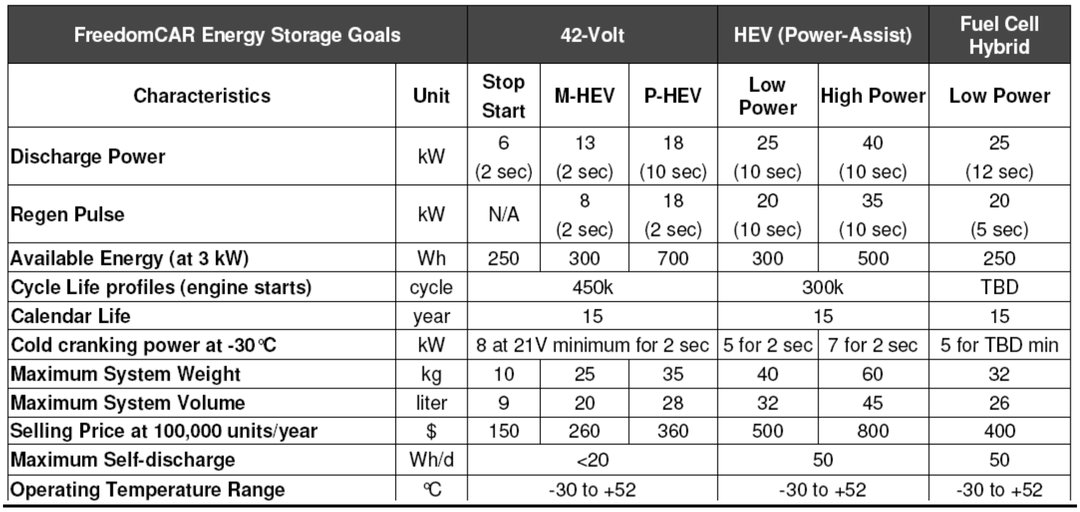
Table 1: characteristics of battery technologies.

		energy storage technologies			
characteristics	*unit*	PbAc	NiMH	LiIon	ultracapacitor
cell voltage	[V]	2.1	1.2	3.6	2.5
efficiency		85	80	93	97
energy density	[Wh/l]	50 - 70	200	150 - 250	5
specific energy	[Wh/kg]	20 - 40	40 - 60	100 - 200	5 - 20
specific power	[W/kg]	300	500 - 1300	800 - 3000	15000
temperature range	[°C]	-30 - 60	-20 - 50	-20 - 55	-30 - 65
self discharge	[%/month]	4 - 8	20	1 - 5	30
number of cycles	@ 80% DoD	200	> 2500	< 2500	/
costs	[$/kWh]	150	500	800	2000
	[$/kW]	10	20	50 - 75	50

source: Advanced Automotive Battery Conference 2005

Arsenal Research 2006, Dr. Valerio Conte

Table 2: characteristics of HEV configurations.



FreedomCAR Energy Storage Goals		42-Volt			HEV (Power-Assist)		Fuel Cell Hybrid
Characteristics	Unit	Stop Start	M-HEV	P-HEV	Low Power	High Power	Low Power
Discharge Power	kW	6 (2 sec)	13 (2 sec)	18 (10 sec)	25 (10 sec)	40 (10 sec)	25 (12 sec)
Regen Pulse	kW	N/A	8 (2 sec)	18 (2 sec)	20 (10 sec)	35 (10 sec)	20 (5 sec)
Available Energy (at 3 kW)	Wh	250	300	700	300	500	250
Cycle Life profiles (engine starts)	cycle	450k			300k		TBD
Calendar Life	year	15			15		15
Cold cranking power at -30°C	kW	8 at 21V minimum for 2 sec			5 for 2 sec	7 for 2 sec	5 for TBD min
Maximum System Weight	kg	10	25	35	40	60	32
Maximum System Volume	liter	9	20	28	32	45	26
Selling Price at 100,000 units/year	$	150	260	360	500	800	400
Maximum Self-discharge	Wh/d	<20			50		50
Operating Temperature Range	°C	-30 to +52			-30 to +52		-30 to +52

source: IBA-Hawaii Battery Conference 2006

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Figures

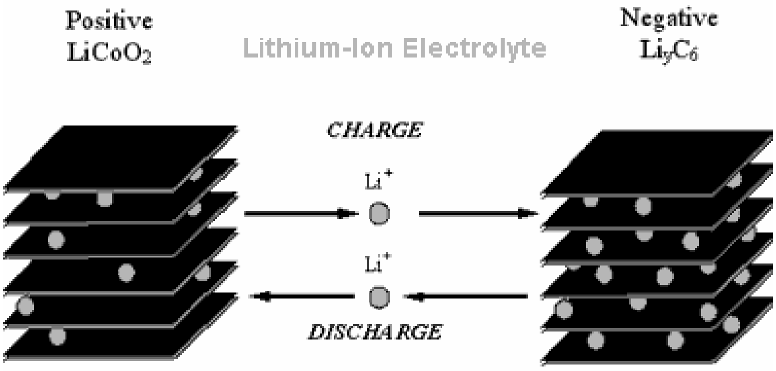

Figure 1: LiIon charge and discharge process (source: MPower).

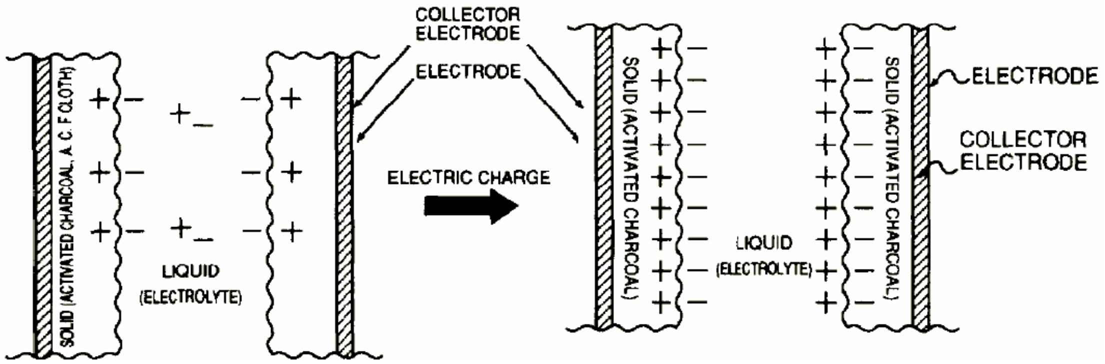

Figure 2: working principle ultracapacitor (source: University of Technology Sidney).

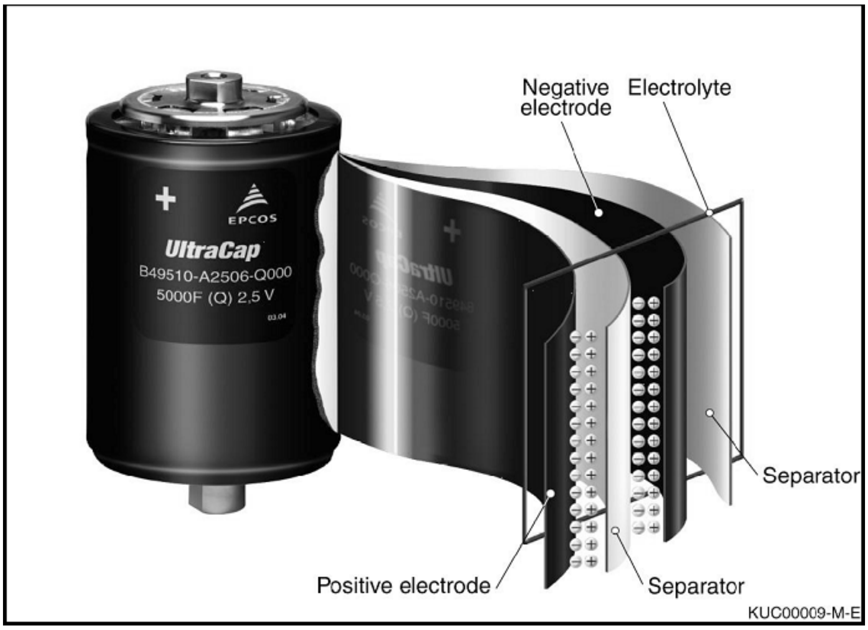

Figure 3: ultracapacitor layer structure (source: Epcos).

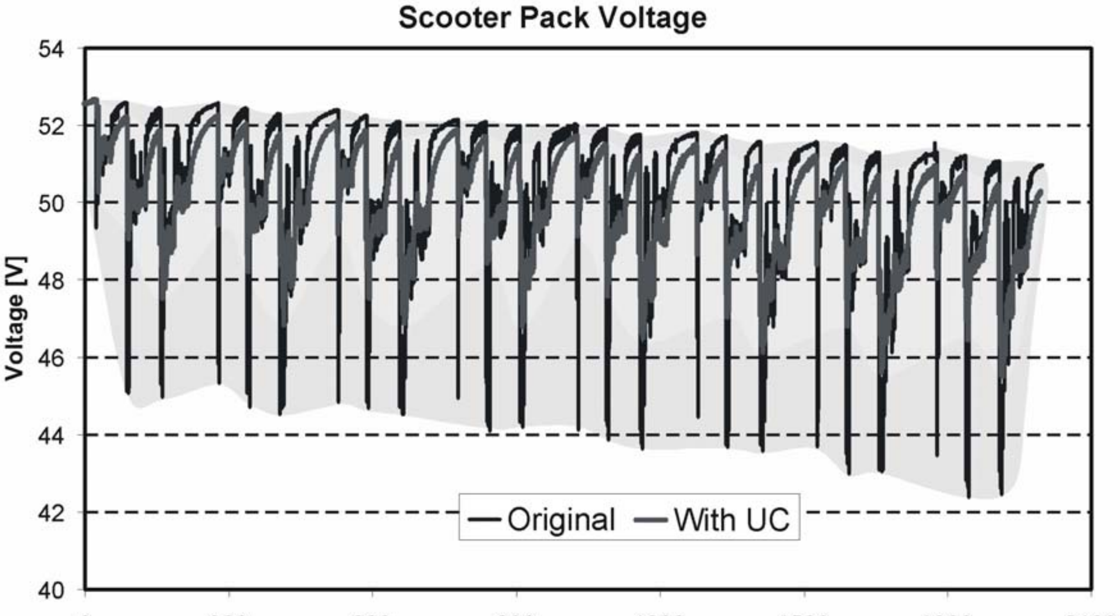

Figure 4: voltage range for a battery pack only and a combination of batteries and ultracapacitors (source: VITO).

Short Biography of Stefan Smets

In 2004, Stefan Smets graduated as Master in Mechanical Engineering at the Catholic University of Leuven in Belgium. In co-operation with Tenneco Europe he made a dissertation about “Measurement and analysis of shock absorber valve dynamics to optimize NVH performance of passenger cars”.

He worked for 2 years as design and development engineer for Tenneco Europe. The main responsibilities covered modular assembly components for different projects and general air suspension. In April 2006 he joined the team Vehicle Technology of Vito as researcher. Since then he has been involved with the development of hybrid systems and technology.

Short Biography of Patrick Debal

In 1985, Patrick Debal graduated as Master in Mechanical Engineering at the Catholic University of Leuven in Belgium. In co-operation with Ford of Europe he made a dissertation about “Comprex Supercharging of Diesel Engines”.

He worked for more than 10 years at several levels in product development and R&D for industry leaders like Atlas Copco. In January 1999 he joined the team Vehicle Technology of VITO as Senior Researcher. Since then he has been in charge of or involved with the development of hybrid systems and technology, on-board emission measurement and with vehicle energy and emission simulation models. During the last few years he has been focusing on the development of new and improved powertrain technology.
