# Modern Battery Systems for Plug-In Hybrid Electric Vehicles

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## Abstract

Plug-in hybrid electric vehicles (PHEVs) are gaining increasing interest for both individual transportation and commercial applications. With the recent technical progress Li-Ion batteries are on their way to open new ways for the future of all type of Hybrid Electrical Vehicles, Mild Hybrids, Full Hybrids and especially Plug-In Hybrids. They are going to replace other battery systems because of their advantages with regard to specific and volumetric power and energy. Earlier limitations of life endurance could be overcome. Ten years life in an automotive specific environment is no longer a problem. Capacity turnover figures are exceeding 20,000 NC (define NC) at DoD values of less than 3% (Full Hybrids) and over 2,000 NC at DoD values of 80% in the electric mode phase of the PHEV drive pattern. Advancements in cell design, material selection and battery sub-system technology have contributed to make Li-Ion batteries systems abuse tolerant.

The presentation is going to cover modern PHEV hybrid battery concepts and reference projects in the field, performance limits of the electrochemistry, cost projections for PHEV battery systems and the development of battery management systems.

**Keywords:** Plug-In, Sprinter, Li-Ion, batteries, battery systems

## 1. INTRODUCTION

Automakers recognize a market eager to reduce fuel costs for transportation. In the United States, the President’s Advanced Energy Initiative emphasizes energy security by seeking to displace crude oil derived motors fuels with energy from renewable, domestic sources, e.g. ethanol and electricity. In a recent study from the California based Electric Power Research Institute (EPRI) the U.S. national average cost of electricity is calculated at $ 0.085 per kilowatt-hour [2] which results for a mid-size PHEV drive train layout in an equivalent of roughly $0.75 / gallon of gasoline compared to the US national average cost of gasoline of $3/gallon. This gives the PHEV a big chance, if cost targets for the electrical drive drain and the battery can be met.

There has been a tremendous amount of progress in the development of battery technology for Hybrid Electric Vehicles (HEV) in the last decade. While battery development for HEV applications has benefited from parallel developments done for portable applications, there are some specific areas of focus that differentiate automotive applications from portable applications. Two of these areas are weight efficiency and battery life. Weight savings is important in vehicle design since the battery weight can offset a certain part of the fuel savings achieved by a transition from conventional drive train to an HEV. The demands for battery life in an HEV application are to achieve ten years or more compared to relatively short expected life of a battery in portable applications. These strong demands to reduce weight and increase life are the reasons most battery development activities are being focused on Li-Ion battery technology.. While there is still considerable room for improvement, it is clear that Li-Ion will be the preferred technology for the next generation of HEV applications due to its ability to provide twice the specific power compared the present NiMH technology

As **Figure 1** illustrates, applications for heavy-duty batteries in the automotive sector can differ by several orders of magnitude concerning energy and power requirements. The battery rating for the individual application directly results from the customers' demands concerning energy content, power and the operating voltage window. This leads to specific requirements for the cell and module designs. Currently, hybrid electric applications for cars and commercial vehicles are of special interest to the manufacturers of batteries. A trend towards larger volumes is discernible. Purely battery powered electric vehicles are still a niche market, but may become more interesting in the mid to long-term future. **Table 1** summarizes typical requirements for different automotive applications.

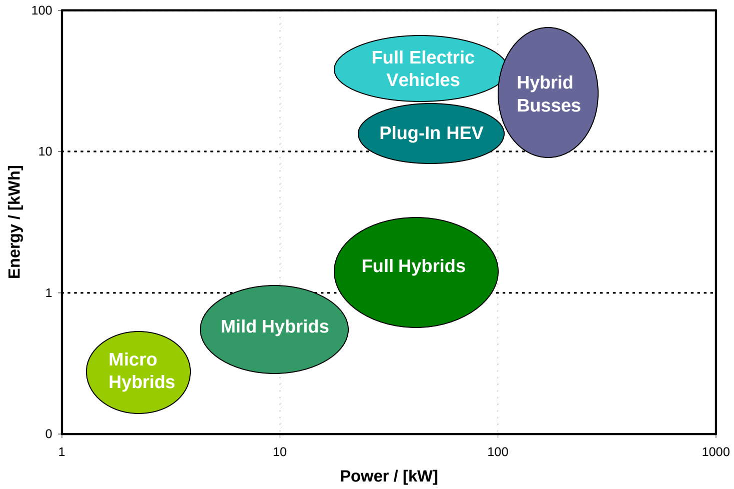

**Fig. 2: Energy and power demands in battery systems for different vehicle applications**

| **Application** | **Electric Range** | **Energy / Power Requirements** |
|---|---|---|
| Electric vehicle | > 150 km range | > 20 kWh / > 40 kW |
| Plug-In HEV | limited range | > 10 kWh / > 40 kW |
| Hybrid Bus | limited range | > 10 kWh / > 80 kW |
| „Full Hybrid“ car | No electr. range | 1 to 3 kWh / 25 to 50 kW |
| „Mild Hybrid“ car | No electr. range | 0.5 to 1 kWh / < 20 kW |

**Tab. 1 : Automotive applications and demands on the battery system**

The choice of a suitable energy storage system is based on six major characteristics inherent to the system:

- specific energy content
- energy density
- specific power
- power density
- maximum useable capacity or energy performance
- calendar life

## 2. LITHIUM-ION BATTERIES

Lithium Ion batteries are the most promising and dynamic field of development in battery technology today. After they have successfully prevailed in the battery market for high technology portable applications, it is expected that Li-Ion batteries will take over an increasingly important role in the automotive sector.

Today's serial production hybrid cars are nearly all powered by Nickel-metal-hydride batteries (NiMH), a reliable and abuse tolerant technology for high performance applications in the automotive sector. They are also used for supplying traction systems of hybrid versions in the commercial vehicle range at a smaller scale. From a technical point of view the Nickel-Metal Hydride battery system is considered to have largely exhausted its potential. No further significant developments of its performance data are to be expected. The development is concentrated on optimizing the total system regarding cost, packaging and battery management, just as for lead-acid batteries. The most prominent features of the high power NiMH cells are their specific power of up to 1300 W /kg and the high capacity / energy endurance figures that can be achieved with them (> 20,000 NC at 5%DOD) long cycling endurance.

Plug-In hybrid vehicles, in particular, underscore the value-add of Li-Ion technology. The advantages in both packaging impact and weight reduction potential of over 30% compared to NiMH reveal the potential of Li-Ion technology.

### 2.1 General Characteristics of the Li-Ion System

As is valid for all types of electrochemical storage systems the technical properties of Li-Ion cells very much depend on the specific layout of electrode and cell components. Depending on the special purpose the following list summarizes the generally achievable performance levels.

- high specific power performance of up to 3,000 W/kg (on cell level)
- high specific energy of up to 160 Wh/kg (on cell level)
- high power density up to 6,000 W/ l (on cell level)
- high energy density up to 160 Wh/l (on cell level)
- high energy throughput feasible (dependent on discharge depth)
- high cell voltage and thus reduced number of cells to be connected in the battery group
- no voltage hysteresis, thus theoretically: 100% energy efficiency
- very good long-term behavior (calendar and cycling endurance)
- sensitive to continuous overcharging and short circuiting

- individual cell monitoring necessary

## 2.2 Li-Ion Cells for Automotive Applications

Due to the relatively low conductivity of the organic electrolyte in comparison to aqueous media, electrodes for Li-Ion cells have to be processed in very thin layers, resulting in comparatively complex manufacturing process. As even minute traces of water and oxygen have a permanently damaging effect on the life span of Lithium cells, the impermeability of the cells is of the utmost importance.

The preferred shape of Li-Ion cells is cylindrical with a spirally wound electrode **(Figure 3**). This type has, owing to its large and thus long electrode surface, significant production advantages. Alternatively, there are attempts to implement prismatic designs, which are characterized chiefly by their potential for better . Originally developed as a pure high-energy battery system, Li-Ion has turned out as a versatile system, which can cover a wide range of energy and power requirements. Fig. 3 shows the spectrum of currently available JCS cylindrical cells, which can be used to meet different automotive applications.

A major advantage of Li-Ion electrochemistry is the high voltage of the individual cells, which allows for establishing a battery group with a comparatively small number of cells. All individual cells in such a battery group have to reliably remain within a voltage window of 2.5 V to 4.1 V, however. This calls for an active battery management system.

**Diameter 54 mm / Energy-Power Applications EV or PHEV**

| | VL45E | VL41M | VL22M | VL30P |
|---|---|---|---|---|
| **Capacity (Ah)**<br>C/3 @ 4V | 45 | 41 | 22 | 30 |
| **Dia. (mm)** | 54 | 54 | 54 | 54 |
| **Length (mm)** | 222 | 222 | 145 | 222 |
| **Weight (kg)** | 1.07 | 1.07 | 0.65 | 1.1 |
| **Volume ($dm^3$)** | 0.51 | 0.51 | 0.33 | 0.51 |
| **Energy (Wh)** | 160 | 146 | 78 | 107 |
| **Power (W)**<br>Current limit (A) | 710<br>250 | 850<br>300 | 700<br>300 | 1520<br>500 |
| **Power (W)**<br>V limit, 2.5 V | | | | 2300 |
| | 30s – 50%SOC | | | 10s – 50%SOC |

**Fig. 3a: Li-Ion cells for Electric Vehicle (EV) and Plug-In Hybrid Electrical Vehicle (PHEV) applications with differing requirements in energy storage and electric power**

**Diameter 38 mm / Power Applications HEV**

| | VL6P<br>Gen 1 |
|---|---|
| **Capacity (Ah) - at C/3 @ 4V @ 25°C** | **7** |
| **Diameter (mm)** | **38** |
| **Length (mm)** | **145** |
| **Weight (kg)** | **0.36** |
| **Volume ($dm^3$)** | **0.16** |
| **Energy (Wh)** | **25** |
| **Discharge Power (W)**<br>Current limit (A) | **730**<br>250 |
| **Discharge Power (W)**<br>V limit, 2.5 V | **1000** |
| | **10s – 50% SOC – 25°C** |

**Fig. 3b: VL6P High power Li-Ion cell for various automotive applications**

## 2.3 Power Data and Temperature Dependency

The power performance vs. state-of-charge (SOC) and its temperature dependency of a Li-Ion high performance cell is displayed in **Figure 4**. At operating temperatures of approximately. 30°C, typical during continuous operation, specific power values are at a level of about 2,000 W/kg, which is more than a 50% improvement in comparison to NiMH cells. At lower temperatures the Li-Ion high power cell

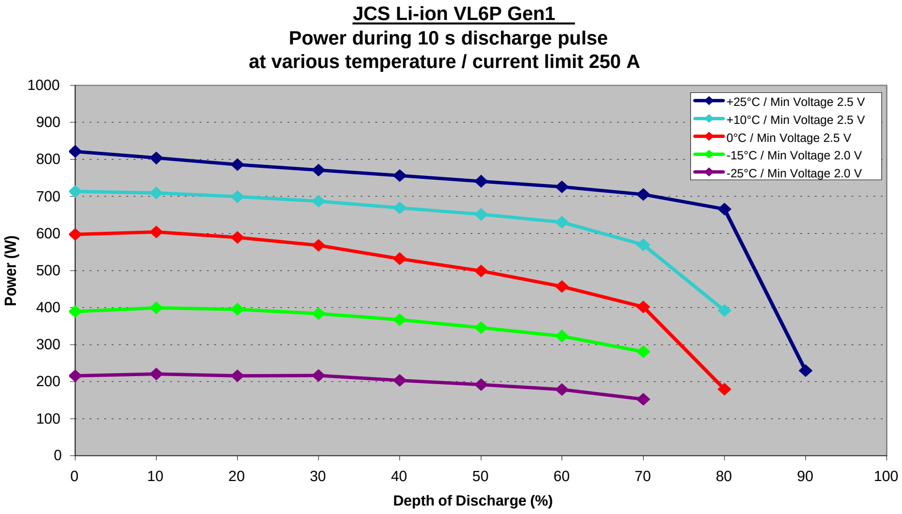

**Fig. 4: Discharge power performance (10s pulse) vs. state-of-charge (SOC) of a High Power VL6P cell at various temperatures**

also has an excellent performance. With approximately 500 W/kg at -25°C, the typical requirements of cold starts have been fulfilled. In contrast to NiMH-batteries the limits of the maximum charging currents have to be observed strictly in the lower temperature ranges, in order not to jeopardize the life span of the battery.

## 2.4. Life Span of Li-Ion Batteries

Where the calendar life span is concerned, major improvements have resulted from the continuous development of active and passive electrode materials as well as from product engineering over the last years **(Figure 5)**. Under real conditions in vehicles today a life span of more than 10 years is considered realistic. Future developments target an extension of the life span to more than 15 years. The results of a cyclic endurance tests (**Figure 6**) with both a Li-Ion VL41M cells designed for Plug-In hybrid applications and a parallel test done with NiMH batteries with the same energy storage capability. are shown in **Figure 7**. Besides more than 20% higher power performance the Li-Ion system is capable of a typically 20% longer service life under PHEV conditions. Demands on the capacity throughput of PHEV batteries are completely fulfilled.

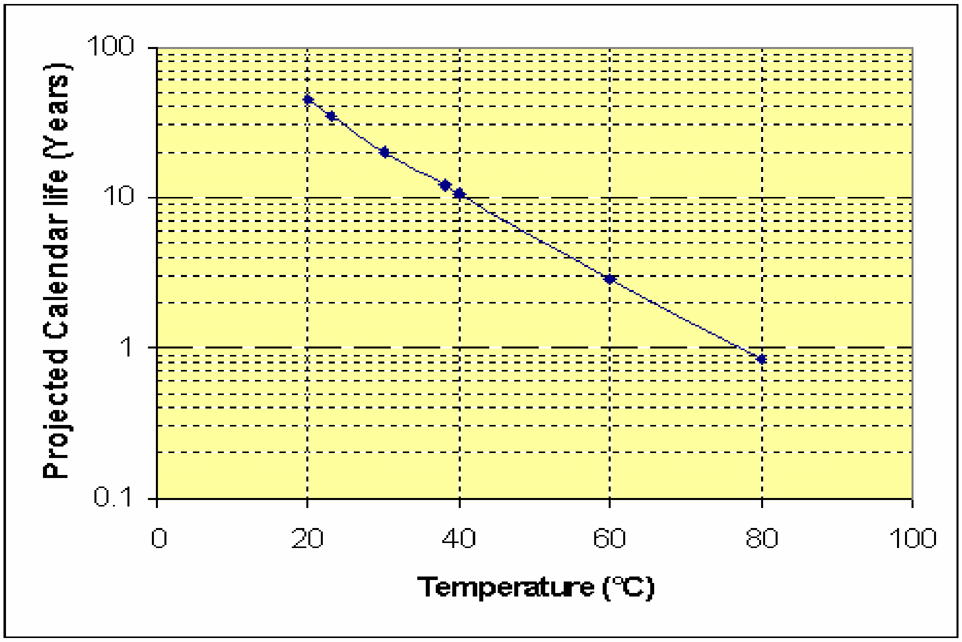

**Fig. 5: Life span of Li-Ion cells as a function of the storage temperature (60% SOC)**

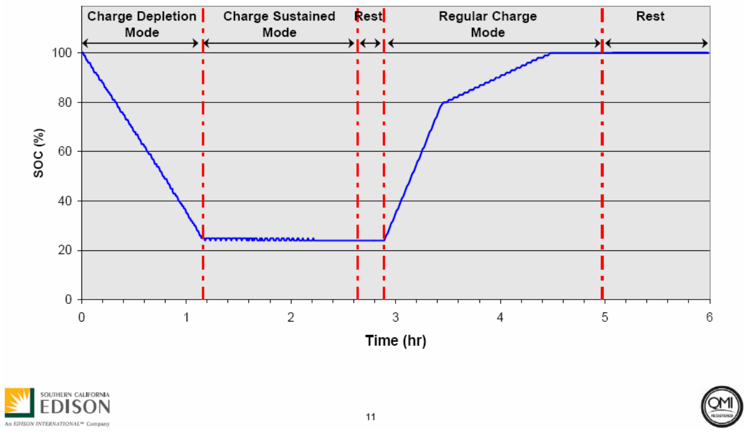

**Fig. 6 : Test cycle for Plug-In HEV duty profile (80% DoD)**

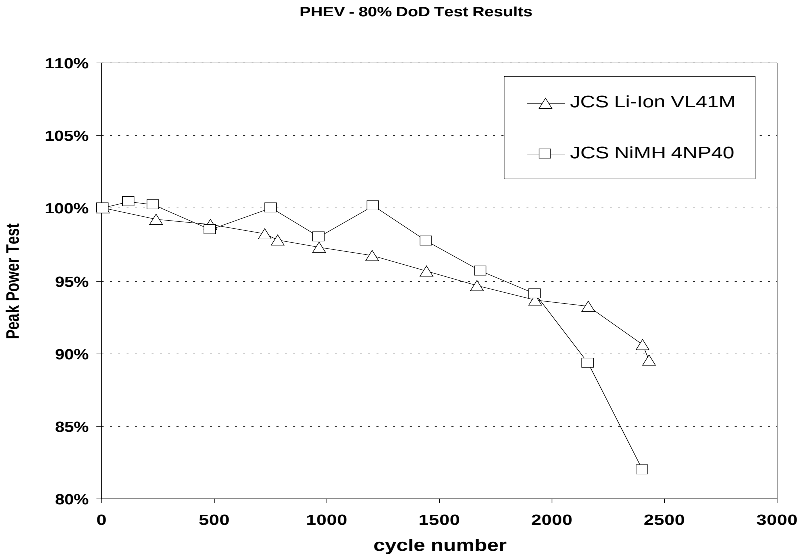

**Fig. 7 : Result of a life test under PHEV cycling conditions (80% DoD) with a battery subsystem system based on Li-Ion VL41M cells and NiMH NP40M cells conducted by Southern California Edison (Status Sep 2007)**

## 2.4 Li-Ion Battery Systems

In order to satisfy requirements for longevity, reliability, and abuse tolerance, Li-Ion batteries must be designed as integrated systems including provisions for thermal management, battery management (software and hardware) and physical enclosure. To ensure predictable performance under abusive conditions such as overcharging, excessively deep discharge, and short-circuiting, the battery management system is of vital importance. NiMH-modules, which show a certain tolerance in cases of over and deep discharge, are monitored in larger partial groups, for Li-Ion batteries, the individual cell voltages are monitored. Any differences in the charged state are balanced by an active charge state management, in order to keep the cells permanently in an optimum charge SOC uniformity window. An efficient cooling system has been provided to dissipate the heat generated during continuous operation, which keeps the cells in the battery group at a uniformly low temperature level. In **Figure 8** the schematic setup of a Li-Ion battery system is depicted.

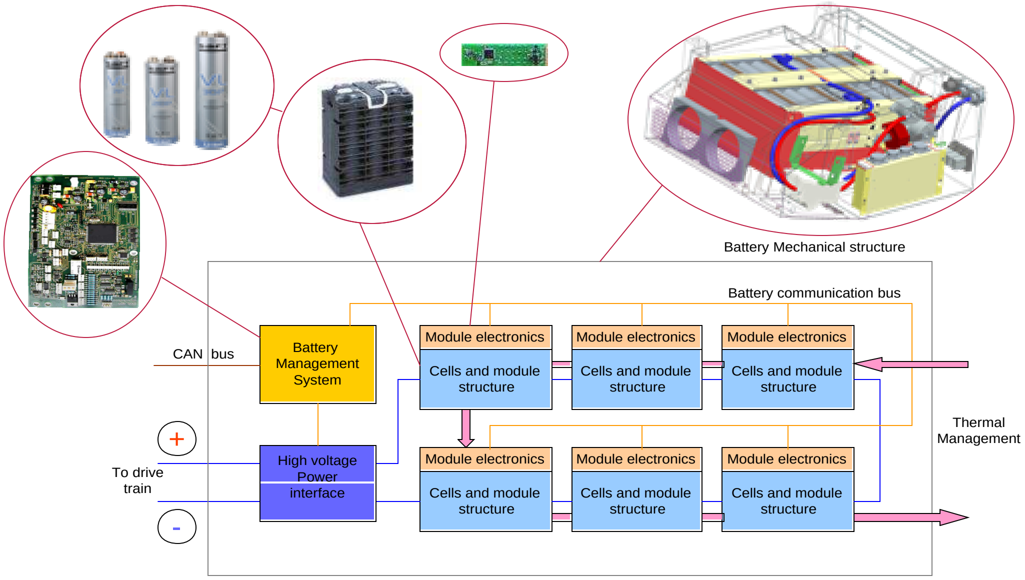

**Fig. 8 : Schematic setup of a Li-ion battery system with electric and thermal management**

The technology primer of PHEVs is the DaimlerChrysler Sprinter Delivery Van [3]. It contains a 14 kWh Johnson Controls – Saft Li-Ion hybrid battery system and is being introduced into a fleet which will be operating within the United States. The test fleet is helping to usher in a new age of extremely fuel-efficient and environmentally friendly, urban transportation. The Li-Ion battery packs in Sprinter plug-in hybrids will be over 40 percent lighter compared to previous NiMH PHEV systems while delivering more power. For HEV's with power-assist-hybrid drive trains, Nickel-Metal-Hydride is a mature technology in use in over 500,000 HEV vehicles in the field.

The Johnson Controls – Saft Plug-In fleet project with the DaimlerChrysler Sprinter platform covers in the first generation with two system solutions: 1) NiMH (14.4 kWh, 300 kg, 530 dm3 ), and 2) Li-Ion (14 kWh, 200kg,170 dm3). The 2nd generation built into a fleet of 20 vehicles will be a Li-Ion solution-only realizing a reduction potential of 15% compared to Li-Ion Gen I (14kWh, 170kg, 122 dm3). The additional reduction potential is realized by a complex system integration utilizing DaimlerChrysler's waver cooler( do you mean liquid cooled?) concept.

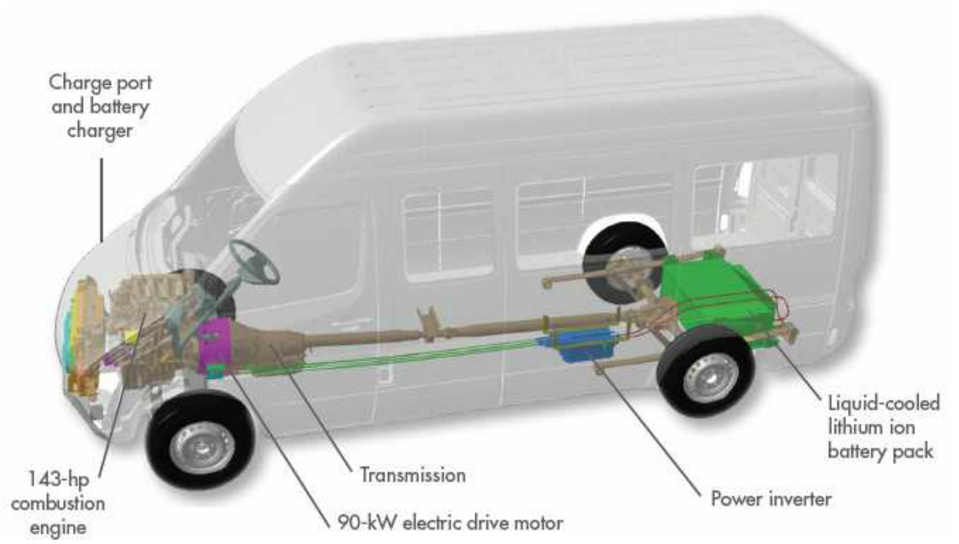

**Fig. 9: PHEV Technology Primer Dodge Sprinter with JCS Li-Ion hybrid battery system**

## 3. COMPARISON WITH OTHER BATTERY SYSTEMS

**Figure 10** shows a graph, comparing the performance of different energy storage systems: lead-acid, NiMH, NiCd, Li-Ion and super capacitors concerning the requirements of specific energy and specific power. This Figure clearly demonstrates the advantages of the Li-Ion system. Proven functional performance, abuse tolerance, and commercial availability are the reasons Nickel - Metal Hydride is the dominant system for hybrid automotive applications today. The Lithium-Ion system has major advantages for defined specific energy storage capabilities and specific performance in comparison to the NiMH-system.

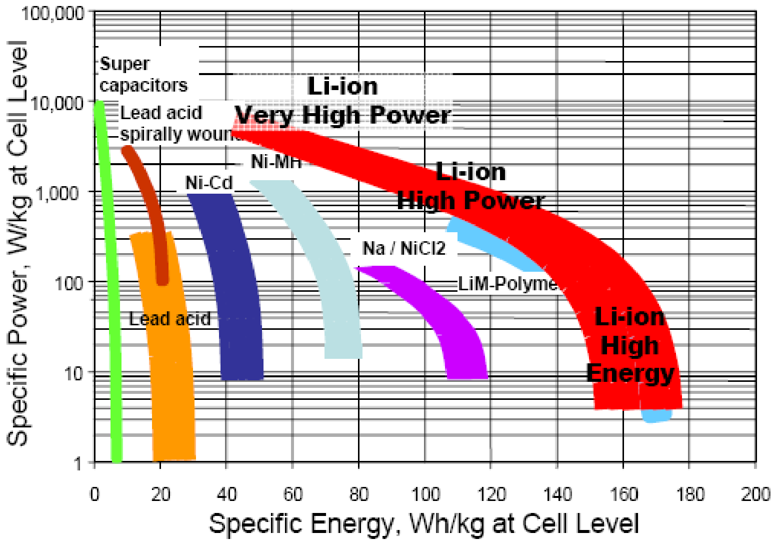

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**Fig. 9: Ragone plot: Specific power and specific energy of different energy storage systems**

The life span of the battery system - calendar or as capacity turnover – is of crucial importance for the operating efficiency in automotive applications. The feasible capacity throughput is largely determined by the charging and discharging conditions. **Figure 10** shows the dominating influence of the discharge depth on the maximum capacity turnover of different battery systems operating under different DOD cycling conditions. As indicated in Figure 10, the cyclic durability of Li-Ion is equivalent to or better than the other chemistries.

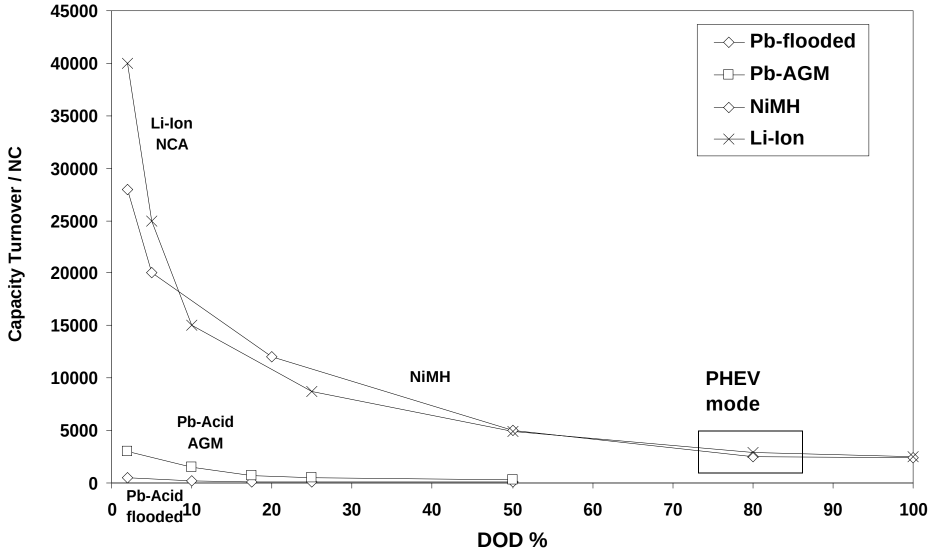

**Fig. 10: Capacity throughput of different battery technologies as a function of the discharge depth**

For applications making extreme demands on power and service life, high performance super capacitors are being developed. However, super-caps to typically exhibit rather low specific and volumetric energy densities,. Cost and weight of the power electronics necessary for the management of the steep voltage characteristic severely limit application feasibility up to now. By comparison , electrochemical storage systems generally provide more energy at more stable voltage levels.

## 4. SUMMARY AND PERSPECTIVES

Mini-hybrid applications, such as Start-Stop systems, will continue to be served by Lead-Acid-batteries, due to reasons of economy. Lead-batteries are relatively favorably priced due to the relatively low cost of the raw materials, which makes them the preferred solution for standard automotive applications, where range and life requirements are modest. For hybrid cars, the Nickel-metal-hydride system provides a battery technology that has been proven in years of service. The system is considered largely exhausted from a technical point of view. As the price of Nickel is a significant cost factor, an increase of commodity prices is a critical issue and efficient recycling procedures constitute an important challenge.

In contrast to the aqueous Pb-acid and Nickel-metal hydride systems, Li-ion shows strong potential for substantially superior performance. Whereas the NiMH-system offers an upper technical limit of specific power of approximately. 1500 W/kg , the Li-Ion system still has room for significant growth, e.g. the specific power will increase to values clearly above 3,000 W/kg, enabling much lighter, and smaller, systems solutions with easier packaging. Current actions concerning material development, systems engineering and manufacturing processes will also continue to contribute to improve the prerequisites for an economic automotive application.

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