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Review

Systems for hybrid cars

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Abstract

Not only sharp competition but also legislation are pushing development of hybrid drive trains. Based on conventional internal combustion engine (ICE) vehicles, these drive trains offer a wide range of benefits from reduced fuel consumption and emission to multifaceted performance improvements. Hybrid electric drive trains may also facilitate the introduction of fuel cells (FC). The battery is the key component for all hybrid drive trains, as it dominates cost and performance issues. The selection of the right battery technology for the specific automotive application is an important task with an impact on costs of development and use. Safety, power, and high cycle life are a must for all hybrid applications. The greatest pressure to reduce cost is in soft hybrids, where lead-acid embedded in a considerate management presents the cheapest solution, with a considerable improvement in performance needed. From mild to full hybridization, an improvement in specific power makes higher costs more acceptable, provided that the battery's service life is equivalent to the vehicle's lifetime. Today, this is proven for the nickel–metal hydride system. Lithium ion batteries, which make use of a multiple safety concept, and with some development anticipated, provide even better prospects in terms of performance and costs. Also, their scalability permits their application in battery electric vehicles—the basis for better performance and enhanced user acceptance. Development targets for the batteries are discussed with a focus on system aspects such as electrical and thermal management and safety.

Keywords: Hybrid electric vehicles; Battery storage systems; Battery management

1. Introduction

Hybrid electric vehicles (HEV) are currently considered the most viable alternative propulsion system. Depending on the degree of electrification, the combination of the internal combustion engine (ICE) with an electric motor in the hybrid drive train offers a wide range of improvements from most efficient fuel consumption and emission reduction to enhanced power performance. In contrast to fuel cell (FC) vehicles which make use of hydrogen or methanol, no new infrastructure is required. Yet the HEV may, in the long run, facilitate the introduction of FC vehicles because of the progress anticipated in the development of both the battery and the electric drive train as the common components of the HEV and the FC–HEV [1].

The electrical storage system is the key element of the HEV components, because its power and life decisively define the costs of the overall system. The recent development of high specific power batteries allows small size, low weight storage systems to be set up, thus opening the way for parallel HEV. They will be discussed in some more detail later in this paper.

Fig. 1 provides an overview of the storage system technologies with their respective vehicle applications as discussed in this paper. In addition to the parallel ICE–HEV application, on the low (absolute) power side the belt-driven starter-generator (BSG) and integrated starter-generator (ISG) functions are covered, while on the high power side the all-electric FC–HEV and the battery electric vehicles (BEV) are mentioned.

The proper selection of the battery technology for the specific automotive application is a burning issue, since it affects the costs of development and of use. Awareness of the varying working conditions in real life and the desire that the battery service life be the same as the vehicle life, true-life testing no longer meshes with quick decisions. Accelerated-life testing and transfer of experience gained with similar applications are needed to assess the battery systems, sustained by the knowledge of the battery chemistry. Also, an electrical and thermal management is required to ensure optimum working conditions and, of course, for safety.

2. Hybrid systems

As mentioned, development is currently focusing on parallel hybrids, because they provide an acceptable cost-to-benefit relationship. The designations of the various

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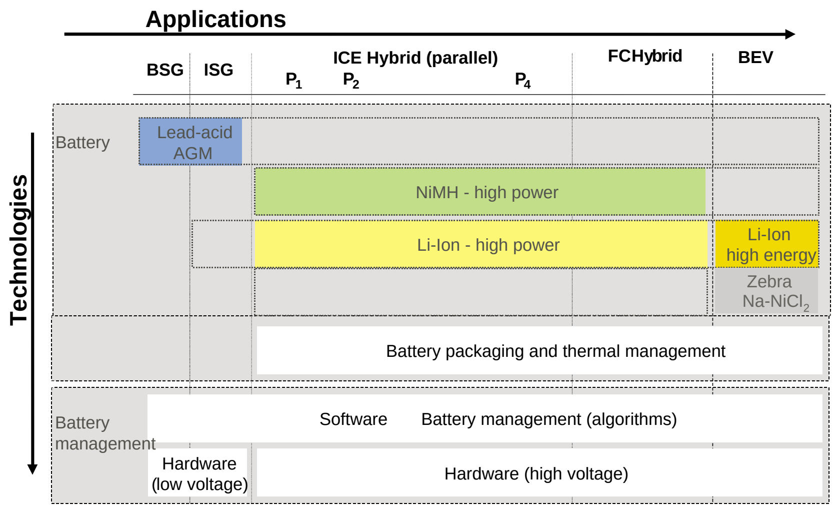

Fig. 1. Storage system technologies and their vehicle applications.

arrangements of the motor in the drive train are typically not common knowledge for battery specialists: therefore, they are depicted here for reference (Fig. 2).

In the P1 and P2 configurations, the electric motor has the same rotation speed as the ICE. With the placement in P3 and, basically, in the P4 configuration also, the rotation speed is defined by the transmission shaft. With the motor on the axle that is not powered by the ICE, P4 constitutes a four-wheel drive with the hybrid power provided "through the road".

In the parallel HEV drive train, the electrical drive components contribute power—preferably when the ICE works inefficiently or if a "power boost" is needed. However, the motor power represents only a part of the total power and enables the size of the electrical components to be tailored to the requirements. With an increasing degree of electrification, we can define the following main applications:

- stop-start;

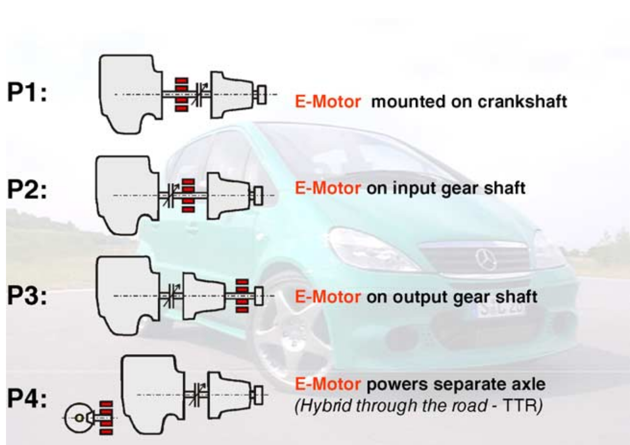

Fig. 2. Chief types of parallel hybrids.

- mild HEV (42 V); and
- full HEV (300 V).

In the following sections, the requirements placed on the batteries by these applications are discussed.

2.1. Stop-start

The stop-start function marks the low end of hybridisation. Electric propulsion is limited to a velocity of the vehicle corresponding to an enhanced idle rotation speed of the ICE of 700–1000 revolutions per minute (rpm) on start. As Fig. 3 illustrates, the main task for the battery is to supply the power demand during the stop phases, where the ICE is shut off.

Fig. 3 depicts the power profile for a vehicle performing the new European driving cycle (NEDC). Depending on the extras and ambient conditions, anywhere from 800 to 1500 W have to be delivered during the stop phases: 1000 W will produce 1000 kWh of energy throughput within 4 years and 50,000 km of driving. And depending on the type of starter-generator used (see Fig. 1), there is substantial potential to regain energy by regenerative braking.

Due to the limited power of the BSG of 3–4 kW, this 42-V system is used solely at sufficiently mild temperatures. A conventional 12-V starter battery and starter help to start the engine at temperatures as low as −25 °C. The utilization of regenerative power is limited.

With the ISG system and 42 V only, the cold cranking requirements of approximately 6 kW for 15 s at −25 °C also have to be met by the battery. This in turn well describes the limits of the present AGM-VRLA (absorptive glass mat: valve-regulated lead-acid) technology:

- calendar life ∼4 years;
- 800–1500 W on stop, 1000 kWh energy throughput, 50,000 km; and
- cold cranking power: 6 kW, 15 s at −25 °C.

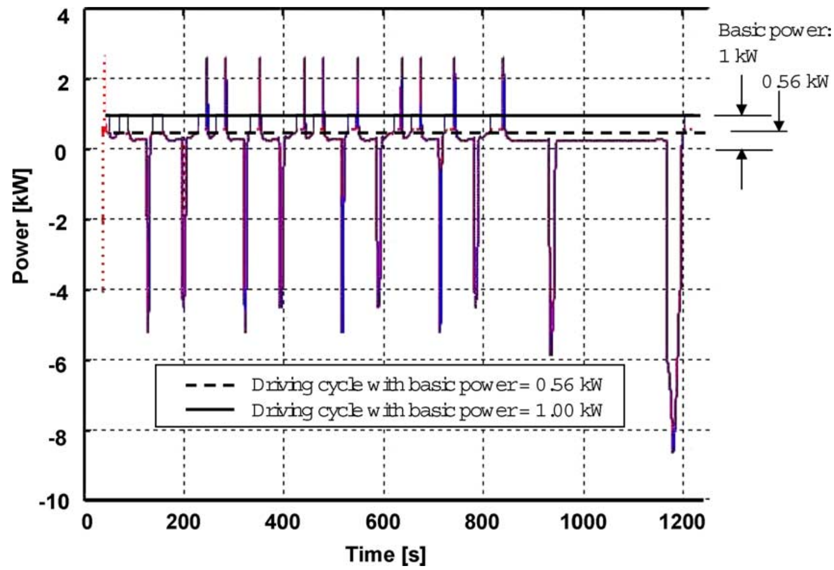

Fig. 3. Power requirements for the stop-start function (NEDC).

Achieving these life data necessitates an elaborate battery management and monitoring system considering refresh (or top-up) cycles and a battery state-of-health monitoring and display for reliable performance [2]. The depth-of-discharge (DoD) must not exceed 1%.

2.2. Mild hybrid

With the mild hybrid function, the acceleration of the vehicle is sustained by the motor and electric drive with substantial power. Fig. 4 sets out the simulated power requirement for a 1200-kg sedan during the NEDC.

Notably, from these power requirements currents of approximately 500 A result. These, in turn, represent approximately the reasonable limits of the 42-V power net. On the other hand, this allows most of the regenerative braking energy offered during the NEDC to be utilized.

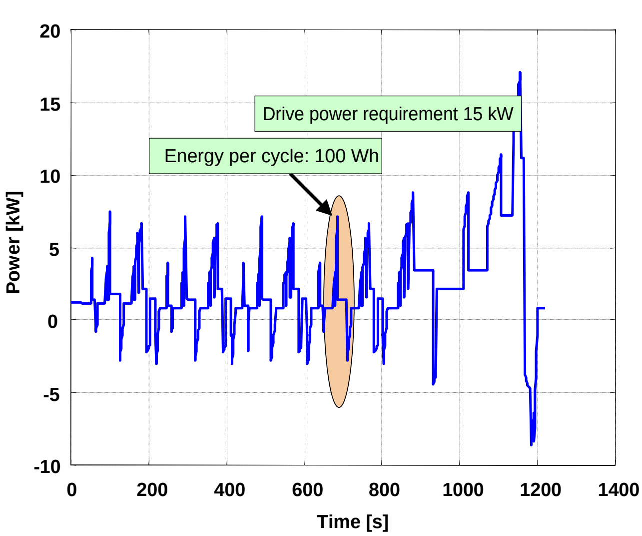

Fig. 4. Power vs. time estimate for the mild hybrid function in NEDC for 1200-kg sedan.

In summary, the battery requirements derived from the propulsion system perspective are as follows:

Battery data	
Voltage	42 V
Peak power	15 kW for 18 s
Power, −25 °C	6 kW for 15 s
Energy content	1 kWh
Weight	<20 kg
Cycle life	>500 k, ±3% DoD
Calendar life	15 years

An example of such a system has been presented on the prototype level [3].

2.3. Full hybrid

Naturally the full hybrid is best suited to shift the electrical power via the battery to where it can be used most efficiently or effectively. Fig. 5 shows the simulation results of a 1200-kg sedan while performing the NEDC.

In this case, the required battery data are as follows:

Battery data	
Voltage	300 V
Peak power	40 kW for 18 s
Power, −25 °C	6 kW for 15 s
Energy content	1.5 kWh
Weight	<50 kg
Cycle life	>500 k, ±3% DoD
Calendar life	15 years

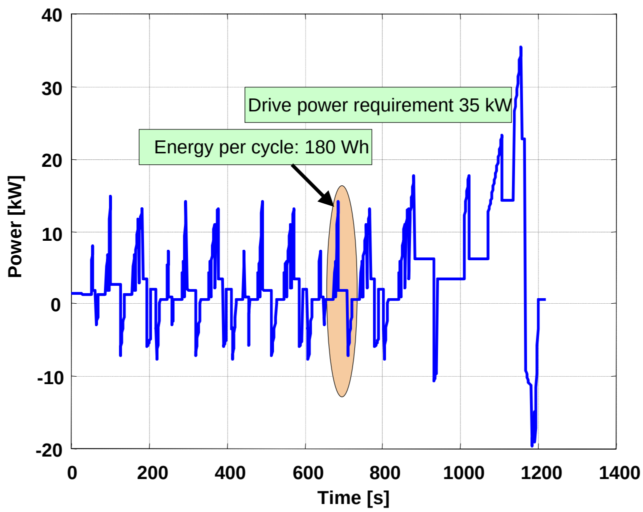

Fig. 5. Power vs. time estimate for the full hybrid function in NEDC for 1200-kg sedan.

It comes as no surprise that these data correspond well with those of the Toyota Prius battery [4].

Hybridization also offers a number of improvements for FC vehicles. Efficiency is enhanced by storing the energy from regenerative braking, which is not possible with the FC alone. As with the ICE–HEV, the battery helps to avoid working regions of poor efficiency, e.g. at low power demand. Therefore, the energy and power requirements do not differ greatly between the ICE- and FC–HEVs. The energy for start-up of the FC and moderate driving performance is easily provided by this type of battery, although at the cost of a somewhat higher depth of discharge (DoD).

2.3.1. Batteries and their applications: lead-acid, NiMH, Li-ion

The following represent our present view as to the usage of battery systems for the HEV applications focused on.

Lead-acid will remain the battery of choice, wherever high cycle life and high DoD are not considered the top performance criteria. Power net applications, up to stop-start functionality, can be served by advanced AGM-type VRLA batteries. This anticipates progress not only in design but also in reliable manufacturing [5] and in battery management. Urgent problems to be solved are stabilizing the PSoC performance and the development of algorithms for reliable SoC and SoH detection [6].

Increasing HEV functions call for batteries with stable cycling performance, together with high power and energy density, as offered by NiMH or Li-ion. Availability and status of development are on different levels. At present, there are pros and cons for both types.

Benefits of lithium-ion over NiMH:

- 30% higher specific energy;
- 50% higher specific power;
- superior cold cranking capability;
- better Wh efficiency;
- 1/3 of the number of cells required for the same voltage; and
- no hysteresis of charge and discharge voltage.

Disadvantages of lithium-ion over NiMH:

- higher system costs for cell supervision, cell equalizing, safety;
- no mass production line implemented; and
- less fleet experience.

Prospects would seem better for the Li-ion system [7]. However, improvement of safety on the cell and battery levels and quantification of the system cost require in-depth consideration and, where necessary, experimental verification.

3. Battery electric vehicles

The battery electric vehicle is the local zero emission vehicle (ZEV) for niche markets such as fleet services or indoor–outdoor delivery. The related battery requirements depend largely on vehicle size and weight.

Assuming an energy consumption of 120 Wh/km in the NEDC, a range greater than 100 km per charge, and 25 kW peak power on driving, the typical requirements for a small vehicle, for example, are set out in Fig. 6.

As the high specific energy battery for such use, only two systems meet the targets: Li-ion and sodium–nickel

Voltage	300V
Energy content	13.5 kWh
Peak power	30 kW
Weight	~120 kg
Cycle life	>1 200
Calendar life	>5 years

Fig. 6. Battery power and energy requirement for a battery electric vehicle.

chloride ($Na–NiCl_2$). Both of these present improved performance over conventional aqueous systems. The achievable range of 200 km offer a better foundation for extending the usable niches for battery electric vehicles.

The $Na–NiCl_2$ battery has a proven history in the battery electric vehicle [8]. In two car integration and fleet test projects funded by the European Commission, a total of 10 vehicles were equipped with Li-ion batteries by Fiat and DaimlerChrysler AG. With the EPIC Minivan EV, a distance of more than 200 km was achieved in the NEDC, and power was supplied almost independent of the SoC of the battery [9].

The ambient operating temperature and the scalability of the Li-ion manufacturing technology with respect to power and size can be considered as an advantage of Li-ion over $Na–NiCl_2$.

4. Battery system requirements

For adequate incorporation of the battery system into the vehicle and an interface to the drive system, a battery management system (BMS) is mandatory. And this feature is paramount for the car manufacturer, since it defines vehicle performance and safety.

The system requirements comprise three elements which are gone into in more detail in the following sections:

- electrical management;
- thermal management; and
- safety measures.

4.1. Electrical management

Fig. 7 sets out the basic topology of a full hybrid or a BEV battery supervision system. It comprises the BMS with the high-voltage (HV) controller to register cell and battery voltages and the battery current galvanically separated from the low-voltage (LV) controller, which transmits the data to the controlled area network (CAN) bus, checks the battery status, and actuates the battery contactors in case of failure. The main task is to keep the battery in good working condition by applying appropriate algorithms. Depending on the battery system requirements, cell or module supervision circuits are used to measure the voltages and transmit them to the BMS. The battery temperature is monitored continually as well. And as a safety measure, the insulator resistance between the battery and the vehicle chassis is monitored. Thus, the BMS supplies the vehicle control unit with data on battery availability and power at intervals of 50–500 ms.

Battery management systems for the 42-V batteries do not require a separate HV controller. Also, just one contactor is used to separate the battery circuit from the drive system.

In general, all the software together with the relevant algorithms for thermal and safety control is also contained in the BMS.

4.2. Thermal management

An HEV battery is often—sometimes within seconds—switched from charge to discharge with multiple charge (C) or discharge (D) rates, thereby producing ohmic losses. The heat produced has to be extracted from the battery to maintain optimum working conditions and prevent thermal runaway and battery death, which may occur within minutes.

Fig. 8 depicts the thresholds of cooling modes presently considered or in use. For the example described, a continuous load on the battery is anticipated.

In general, forced air cooling is the preferred method because of its simplicity and safety in use. Yet there are a number of trade-offs to be considered when designing a battery cooling system: battery size and utilization, in particular, as well as lifetime versus the cost of an effective cooling system such as liquid cooling. In addition, the impact on reliability and safety of the battery system has to be taken into account.

4.3. Safety

Battery safety is one of the most sensitive requirements for battery use. The safety requirements are basically two-fold.

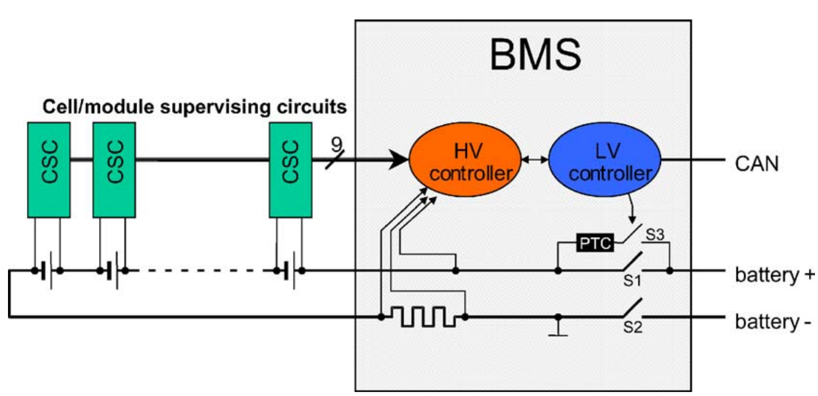

Fig. 7. Topology of the battery management system.

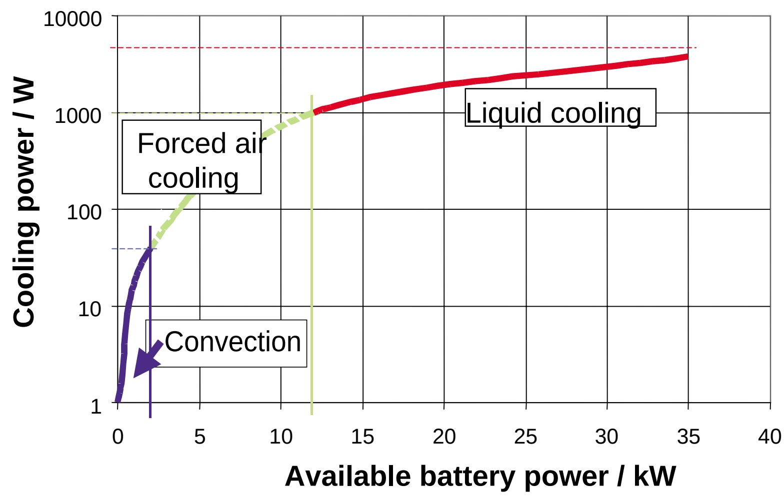

Fig. 8. Battery cooling modes required for continuous battery power output.

1. Full control of the first failure, of all the possible failure modes to occur during operation.
2. In case of crash: no risk for passengers and the environment.

4.3.1. Battery system safety

Basically, the higher the energy content of the battery system, the more safety precautions have to be taken. Lead-acid necessitates only a few: a Bunsen vent, ventilated battery compartments, and a battery monitoring system for failure reporting. The risk potential is restricted to hydrogen explosion, which while it may be serious is commonplace to handle.

NiMH already evidences a proven safety record in HEV but needs some more efforts: with the potential hazards of hydrogen fire, thermal runaway, and hydrogen explosion,

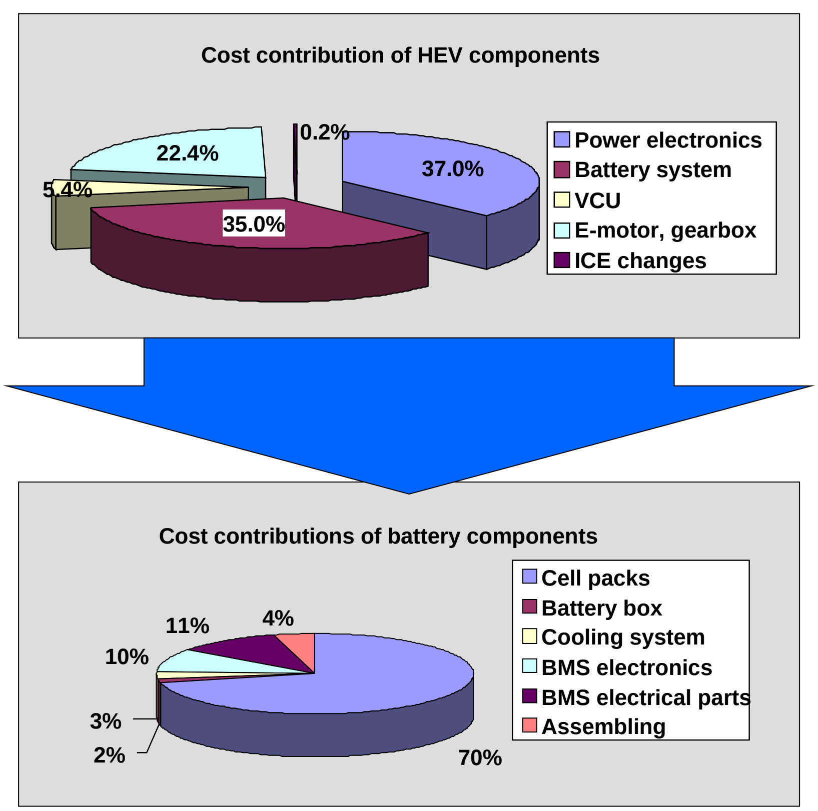

Fig. 9. HEV and battery components cost breakdown.

adequate measures lie in burst disks on the cell level, ventilation of the battery compartment, and a BMS capable of monitoring on the module level.

Due to the high energy density present and the reactivity of the materials involved, the Li-ion system may be subject to electrolyte fire, thermal runaway, and, in the worst case, explosion. For this reason, more, but still affordable safety precautions are needed: burst disks on each cell, a fire-resistant battery tray, and a battery and cell electrical management capable of single-cell supervision and control.

Here, the minimized risk potential of the Li/MnO_2 system versus the Li/NiO_2 system earns mention, as it does not make a fundamental difference for the applications.

In summary, achieving safe vehicle batteries depends on two factors.

1. Inherently safe battery cells:
   - non-flammable solvents, no self-incineration; and
   - leak-before-burst cell design.
2. Modular safety concept:
   - electrical protection against shorts, insulation failure;
   - safety barriers on module and battery containment; and
   - crash-safe packaging and vehicle integration.

4.4. Cost aspects

While safety comes first, cost is the most sensitive item, just like everything else in the automotive industry [10]. For the HEV, the battery system is a main cost contributor, making up anywhere from 1/3 to 1/2 of the HEV system cost. This is illustrated in Fig. 9, which is based on the example of a 300 V, 35 kW NiMH battery system using air cooling.

The battery system comprises cells, container, thermal management system, and the BMS. Of the battery system costs, the cell costs make up 60–70%, while material costs define 80% of cell costs, as the cost breakdown shows. Scale effects achieved with the battery materials thus have a beneficial influence on the battery system costs and are mandatory if the cost targets under discussion are to be achieved.

We anticipate the following costs for the full HEV battery system:

- medium volume: € 1500; and
- high volume: € 1000

And for the mild HEV battery system:

- high volume: € 300

These figures are considered irrespective of the chemistry of the battery system to be used.

5. Conclusions and outlook

The battery system is a key component in the reliable and effective performance of present and future vehicles. The near future will require advanced batteries for various applications:

- starter/alternator;
- hybrids (ICE–HEV and FC–HEV); and
- battery electric vehicles.

For the individual battery systems under consideration, development efforts target different issues.

Lead-acid (VRLA-AGM) batteries:

- stabilizing the PSoC performance; and
- development of algorithms for reliable SoC and SoH detection.

NiMH batteries:

- improvement of low-temperature performance; and
- development of reliable SoC determination algorithms.

Li-ion batteries:

- improvement of cell safety;
- confirmation of cost potential; and
- identification and quantification of the system cost.

To meet the lead-acid issues is prerequisite to keep and improve life time expectations, which the consumer has experienced in the past, when introducing such future applications as stop-start and soft hybridisation being of utmost importance as fuel savers.

The progress in the development of NiMH and Li-ion batteries will decide upon the future market of the systems for HEV and BEV applications.

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