

Performance Plus Range: Combined Battery Concept for Plug-In Hybrid Vehicles

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ABSTRACT

PlugIn Hybrid Electric Vehicles (PHEV) offer the opportunity to experience electric driving without the risk of vehicle break-down due to a low battery charge state. Thus, PHEV's represent an attractive means of meeting future CO₂-legislation.

PHEV batteries must fulfill a divergent list of requirements: on the one hand, the battery must supply sufficient energy to ensure it can be driven an appropriate distance in EV-mode. On the other hand, even with a low state-of-charge (SOC), the battery must supply sufficient power to assist the engine in vehicle acceleration or to recuperate on deceleration. This leads to a compromise in terms of cell selection. Fundamentally, high energy cells cannot provide high charge and discharge rates and high power cells cannot provide sufficient energy. Consequently, the battery can either be provided with the required energy content by switching many power cells in parallel, or it can meet the power requirements with the help of a very large energy battery with a low discharge rate. Neither solution is optimal in terms of the packaging, weight and cost aspects.

This paper presents an innovative and cost-efficient battery concept including customized set-up of the battery through combination of the energy and power modules. The current flow from the battery's energy pack to the power pack and back is realized through a cost-efficient current controller. The combined battery utilizes a predefined current, offering advantages in terms of predicted service life in comparison with conventional batteries. The combined battery provides cost advantages of 12% and weight advantages of 18% compared with conventional battery technology. The current controller offers the flexibility of combining different energy sources which, in turn, permits modular systems to be generated for a wide range of applications with potential scaling effects.

Within this paper, the requirements for PHEV batteries are described along with the concept of the combined battery, the mechanical and electrical layout, as well as the test results of the battery concept on basis of a specific application example.

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1. REQUIREMENTS FOR HYBRID VEHICLES

1.1. Powertrain Layout of a Hybrid-Vehicle

There is a large variety of hybrid vehicle powertrains in the market with respect to principal architecture and the performance layout of the combustion engine/ electric machine(s).

The FEV 7H-AMT is an efficient and cost effective transmission solution for hybrid powertrains. For full- or plug-in-hybrid powertrains, in particular, the installed electric power is significant. A portion of this available power can be used to take automated manual transmission (AMT) shift quality to a new level. The transmission concept is characterized by two main features:

- Uses electrical torque support for all combustion engine gearshifts for vastly improved shift quality compared to conventional AMTs.
- Creates 11 forward gears with only 4 synchronizer units: 8 for the internal combustion engine (ICE), 7 of which are progressively stepped and easily used, and 3 for the electric motor (EM)

The gearset layout enables these features with a unique arrangement of four synchronizer units. As long as one of the idler gears adjacent to the synchronizer unit on the output-shaft is not engaged, this gear can be used to transfer torque from the one input shaft to another. Thereby, the existing gear ratios are multiplied to “generate” new gears. First, third, seventh and reverse gears are “generated gears”, where three gear pairs in a row are used to create the total ratio. To provide electric torque support, the layout includes two independent torque paths to the wheels. During gear shifts, one of the two paths always remains active. During combustion engine gear shifts, the electric motor can fill up the torque gap that would normally exist with an AMT. During all electric motor shifts, the combustion engine continues to drive the vehicle. Figure 1.1 provides a technical overview of the prototype transmission and the performance of the combustion engine and electric motor for which it has been designed.

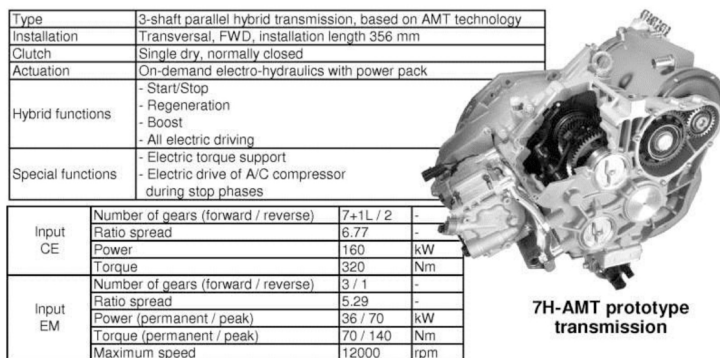


Figure 1.1. Technical overview of 7H-AMT prototype

A measurement from a powered 1-2 upshift is shown in Figure 1.2 as an example of combustion engine shifts with the 7H-AMT. Such a shift can be divided in three approximate phases. In the first phase the torque is transferred from the combustion engine to the electric motor. For a short time span of one second the electric motor can provide up to two times its nominal steady state power. When the clutch has completely opened, the shift fork for first gear is disengaged and second gear is engaged.

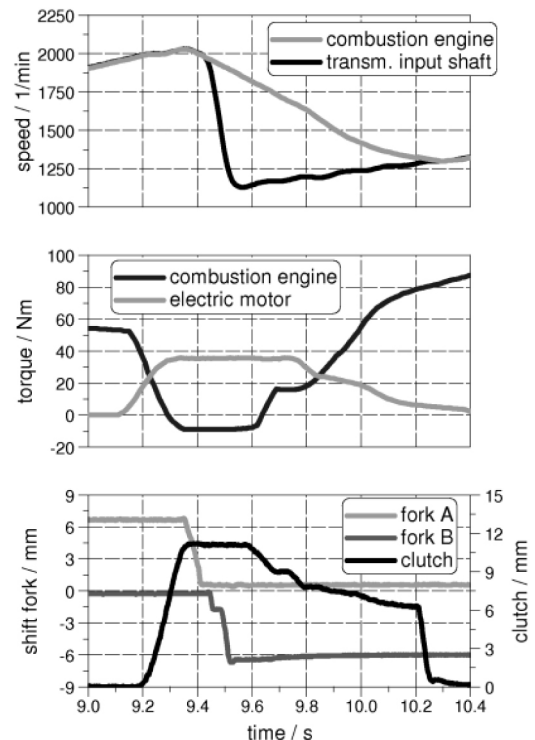


Figure 1.2. Combustion engine shift with 7H-AMT

Because the gearset layout features very low inertia, the synchronizer engagement time is only 30 ms, leading to a total shift fork movement time of 200 ms. In the third phase of this 1-2 ICE shift, the torque is transferred back to the combustion engine again by closing the clutch and decreasing the electric motor torque. This is done via model-based feedback control of the engine speed by regulating the clutch and ICE torque to realize a smooth adaption of the combustion engine speed [3]. The total shift time from opening the clutch until the target engine torque is reached in the next gear is one second, in this example. In this case, electric power of up to a 70 kW peak is required for a duration of approximately 1s.

Since pure electric driving occurs over longer time intervals, the maximum long term power in that case is lower.

1.2. Battery Requirements for a Plug-in-Hybrid-Vehicle

For the purposes of this paper, a battery consisting of a number of cells of the same storage system type is referred to

as conventional battery and a battery consisting of different storage cells, connected by means of a current controller, is referred to as combined battery. The load (PE_{rate}) of a battery

$$PE_{rate} = \frac{P_{batt}}{E_{batt}}$$

is calculated based on the power of the battery P_{batt} relative to its energy content E_{batt} . The relevance of the combined battery for electric Plug-In-Hybrid-Electric-Vehicles (PHEV's) will be shown below. We will start by explaining the requirements for PHEVs. Then, we will apply these requirements to the combined battery and analyze them in terms of power and energy density, service life, and costs.

Today's mobility requirements increasingly focus on urban areas. Today, the average daily trip distance in Germany is approximately 15 km [16]. For commuters, the daily driving distance is roughly 58 km, involving 3.6 trips, and for shopping trips approximately 27 km, consisting of 3.3 trips [16]. The corresponding values for the US are roughly 10 miles in the city and approximately 30 miles in the country [8]. Vehicles that are able to drive this distance while being concurrently environmentally friendly and inexpensive could have a huge market potential. The PHEV can cover a limited distance on purely electric power before the driving power must be generated using fuel energy. From the customer's perspective, the PHEV combines the advantages of a purely electric vehicle (Battery-Electric-Vehicle (BEV)) with the advantages of a hybrid vehicle (Hybrid-Electric-Vehicle (HEV)). Like the BEV, the PHEV can be charged at conventional power outlets. Since PHEVs can be charged at home, power generated by consumers themselves -- for example, through solar cells, combined heat and power plants (CHP), wind turbines, as well as electricity generated in an environmentally friendly way in power plants, can enable these daily trips and make this model attractive for the mass market [8]. If longer travel distances are necessary, the electric drive supports the combustion engine as it does in an HEV. There are two operating mode strategies in a PHEV: Charge Sustaining (CS) and Charge Depleting (CD). Figure 1.3 shows a PHEV battery's state of charge over time. Purely electric driving at the beginning of the cycle is referred to as CD mode, since the battery is supposed to be discharged to the lowest level possible in this mode. After the battery is fully discharged, the vehicle changes over to the so-called CS mode, where the battery has a low state of charge (SOC) and the charge needs to be sustained. Figure 1.3 shows that the conventional battery needs to accommodate short phases of recuperation and acceleration across the entire CD range. This results in the cycle life requirements for PHEV batteries.

In the FREEDOMCAR Plug-In Hybrid Electric Vehicle R&D Plan [4, pg. 23], the energy storage systems of the three main vehicle classes EV, PHEV, and HEV were analyzed in terms of their effectiveness. There, electric vehicles (approximately 80% of their energy content) are operated in CD mode. The remaining 20% is unused energy. A hybrid vehicle, on the other hand, uses a relatively small portion

(approximately 10-15%) of its storage, since it has to be flexible in its reaction to recuperation and acceleration and must, therefore, always have a sufficient amount of charge and discharge reserve (approximately 50%) available. This storage system is primarily operated in CS mode. The requirements for the plug-in-battery are somewhere between these two scenarios and the battery must bridge the gap between a power storage system and an energy storage system. Usually, it uses around 60% of its storage for the CD mode, roughly 10-15% for the CS mode, and the rest remains unused for service life reasons. PHEV's require a relatively high discharge rate, since they must represent the entire output of the drive train. On the other hand, the battery capacity should be relatively small to ensure that the costs and the packaging space will not become too large. General battery requirements for different types of hybrid vehicle classes will be analyzed in detail in References 1, 12, 8, 4 and are shown in Table 1.1.

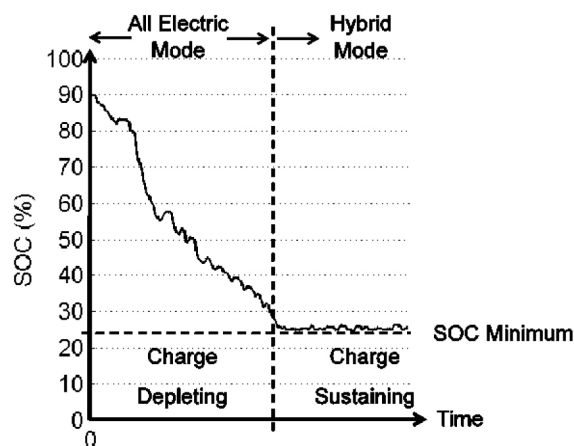


Figure 1.3. Schematic representation of a typical discharging process in the PHEV

Table 1.1. Comparing PHEV Assumptions and Battery "Goals" ([8])

	Units	USABC		MIT	EPRI	
Vehicle Assumptions		PHEV10	PHEV40	MIT30	MIT 20	EPRI60
CD Range	Miles	10	40	30	20	60
CD Operation		All-electric	All-electric	Blended	All-electric	All-electric
Body Type		Cross. SUV	Mid. Car	Mid. Car	Mid. Car	Mid. Car
Total Battery Mass	kg	60	120	60	159	302
Total Vehicle Mass	kg	1950	1600	1350	1664	1782
Battery “Goals”						
Peak Power	kW	50	46	44	54	99
Energy Capacity	kWh	6	17	8	6	18
Calendar Life	years	15	15	15	10	10
CD Cycle Life	cycles	5,000	5,000	2,500	2,400	1,400
CS Cycle Life	cycles	300,000	300,000	175,000	< 200,000	< 200,000

The average energy content (gross) in this case is between 6 kWh and 18 kWh. The average discharge rate is in the range of $3 \text{ (1/h)} < PE_{\text{rate}} < 20 \text{ (1/h)}$. The cycle life in CS mode is specified as $> 300,000$ cycles. With today's cells, this number of cycles can only be reached over a small SOC window. The cycle life in CD mode is specified as $> 5,000$ cycles.

The Ragone diagram below (Figure 1.4) describes the power and energy needed for different types of vehicle classes. The PHEV targets identified by the USABC (United States Advanced Battery Consortium) and MIT (Massachusetts Institute of Technology), as well as a target that was introduced during the FC Expo in 2009, which is regarded as the goal for the "Development of High-Performance Battery System for Next-Generation Vehicles (Li-EAD project)," has also been shown in the figure.

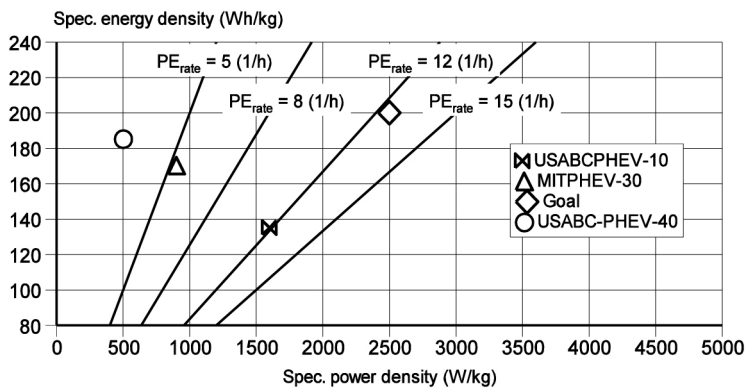


Figure 1.4. Power and energy density requirements for PHEVs (from [8])

A battery can be characterized based on the power density and energy density, factors which can be described using PE_{rate} , the ratio between these two factors. Ideally, it would be desirable to achieve both a high power density and a high energy density. The remainder of this paper is structured on the basis of the most important requirements for achieving this goal. To do this, the special requirements with regard to the PE_{rate} of the battery will be compared with a conventional battery followed by the introduction of the concept of a combined battery. This discussion will be followed by a technical discussion about the service life, the costs, and a comparison of the weight of the batteries.

1.3. Power- and Energy Requirements

As shown in Table 1.1, the requirements for the PHEV10 differ significantly from those of the PHEV40.

A cell specifically developed for each vehicle application is clearly necessary. Once the output requirement for a cell is known, the cell manufacturer can make a cell based on these requirements. To do this, the manufacturer varies the thickness of the electrodes $S_{A,E}$ and $S_{C,E}$ relative to the active material $S_{A,AM}$ and $S_{C,AM}$ (where S refers to Strength, A refers to Anode, C refers to Cathode, E refers to

Electrode, AM refers to Active Material) in consideration of the particular requirements of the application in order to obtain the required output or energy (see Figure 1.4). Power cells are geared towards small internal resistance and energy cells towards relatively high capacitance. A method for adjusting the internal resistance is by varying the thickness of the electrodes and active material layers (see Figure 1.5).

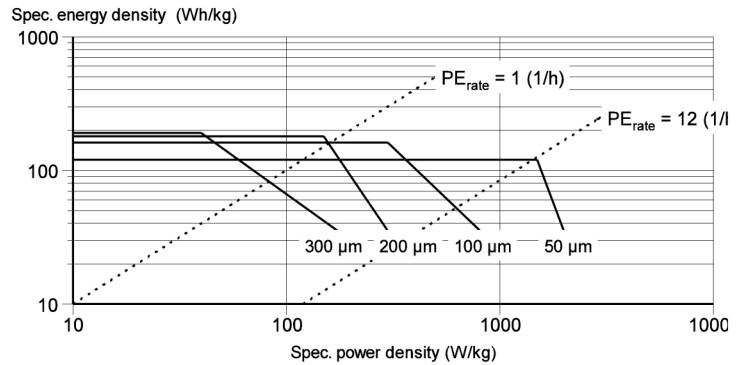


Figure 1.5. Active material thickness over crate based on [5] for a NMC cell

As electrodes become thinner, the travel distances for the electrons and ions through the active material become shorter and the internal resistance becomes smaller. However, concurrent with this change, the energy density decreases, since the fraction of electric current collector material increases relative to the total cell material.

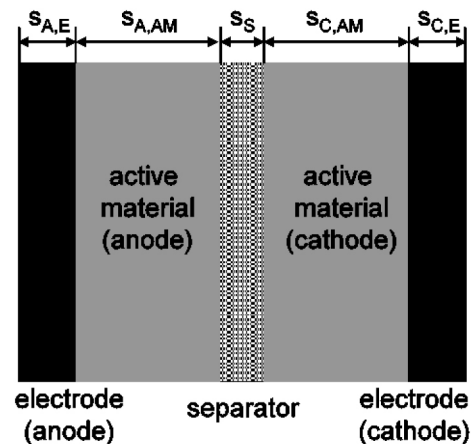


Figure 1.6. Cell design (schematic)

When proceeding in this manner, there is a limitation with respect to the extent to which the active material components can be combined on a cell level.

If two types of storage systems are electrically combined on the battery level, it is possible to combine two cells with the same chemical properties and, therefore, to cover a broad range in the Ragone diagram without the need to develop a new battery cell. Conversely, it is also possible to combine different technologies with high energy density, and high

power density together even if there are different voltage levels.

2. COMBINED BATTERY CONCEPT

The combined battery (FEV Eesy, extended energy system) that has been developed by FEV interconnects storage modules with high-energy cells and storage modules with high-performance cells with the help of a current controller (bidirectional current controller (BCC) - see [Figure 2.1](#)). In the process, the power pack (PP) is directly connected to the inverter of the traction-electric-motor. The energy pack (EP) is also connected to the inverter via a current controller in parallel with the power pack. The current controller regulates the current of the energy pack to a defined value and is designed to ensure that the battery meets the specified performance requirements without a requirement for cooling the energy pack.

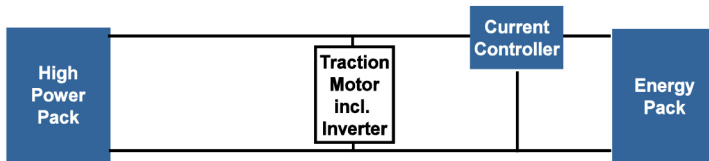


Figure 2.1. Principle of the combined battery

2.1. Cycle Life

Figure 1.2 and Table 1.1 show the requirements for a typical PHEV. The requirements in terms of cycle life in the CS mode differ greatly from those in the CD mode. A small capacity range is used in the CS mode, but high outputs must be provided for a high number of cycles (> 300,000 cycles). A large capacity range is used in the CD mode, but not as many cycles (< 5,000 cycles) are required. [Figure 2.2](#) shows a diagram of the course of the state of charge over one cycle for the combined battery. The power pack is operated in CS mode and the energy pack in CD mode. Therefore, it is possible to combine power cells with a stable cycle life that only use a small SOC range as shown in [Figure 2.3](#) together with high-energy cells in a combined battery.

Currently, the following cells are suitable for the power pack:

- Nickel-manganese-cobalt-based cells,
- Titanate-based cells,
- Iron-phosphate cells,
- Super capacitors.

The following are suitable for the energy pack:
Nickel-manganese-cobalt-based cells,

- Fuel cells,
- New technologies with low power such as lithium metal.

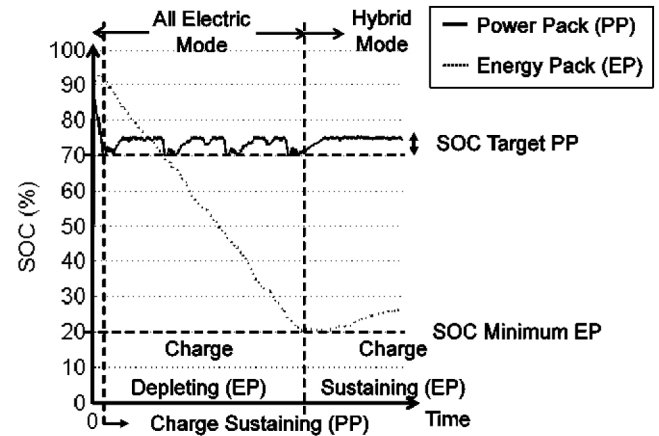


Figure 2.2. Schematic representation of the state-of-charge over one FTP cycle in the PHEV for combined batteries

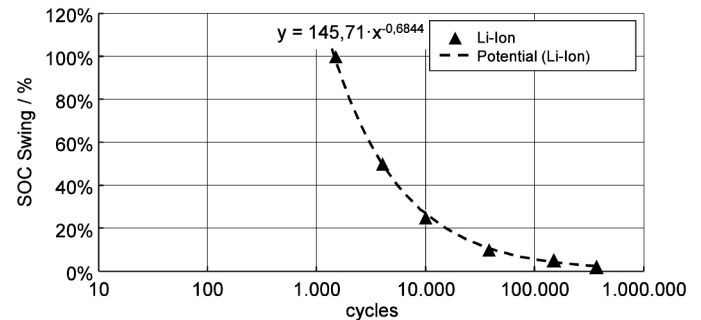


Figure 2.3. Cycle Life over depth of discharge (based on [11, S.45] and [15])

2.2. Costs

It can be more cost-effective to combine small capacity cells as the power battery together with a large energy battery. This will be shown below. A battery must be designed for maximum peak power output and maximum range (energy content). If the maximum PE_{rate} of the power pack and the energy pack is known, then the ideal proportions of the combined battery in term of cost-effectiveness can be calculated.

$$\begin{aligned} P_{batt} &= P_{PP} + P_{EP} \\ &= E_{PP} \times PE_{rate,PP} + (E_{batt} - E_{PP}) \times PE_{rate,EP} \\ &= E_{batt} \times PE_{rate,EP} + (PE_{rate,PP} - PE_{rate,EP}) \times E_{PP} \end{aligned} \quad (2.1)$$

$$\Rightarrow E_{PP} = \frac{P_{batt} - (E_{batt} \times PE_{rate,EP})}{PE_{rate,PP} - PE_{rate,EP}} \quad (2.2)$$

$$\Rightarrow E_{EP} = E_{batt} - E_{PP} \quad (2.3)$$