Battery selection to improve performance of Plug-in Hybrid Electric Vehicles

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***Abstract*—The increasing interest in energy storage systems for Plug-in Hybrid Electric Vehicles (PHEVs) can be attributed to multiple factors, including the capital costs of managing peak and constant demands, energy to weight and power to weight ratios, the charging time, and the operating range they provide, along with several other factors. Although existing energy storage is dominated by batteries, majority of which are Nickel Metal Hydride and Lithium-ion batteries, there is the recognition that various other types of battery systems can offer a number of high-value opportunities, provided that lower costs be obtained. This report takes a look at various types of hybrid electric vehicles, their typical energy requirements and the requirements of energy systems in a PHEV. In the later part, the report deals with the available battery technologies, the fields of battery research that have the potential to serve as a viable medium for PHEVs, as an energy source option.**

Keywords— Hybrid vehicles; plug-in hybrids; batteries;

I. INTRODUCTION

With the growing concern about the devastating condition of the environment in the present days, with on-road motor vehicles contributing about 30.6 percent of volatile organic compounds (VOCs), 34.3 percent of NO_x, and 4.4 percent of particulate matter (PM10) to urban ambient conditions [1], a need to look out and search for alternative methods of vehicular pollution control, other than minimizing the number of fossil fuel driven vehicle consumption, arises. This demand can be partially fulfilled by visualizing hybrid electric vehicles (HEVs) as a replacement for conventional fossil fuel vehicles. While much of research and development has already been done, and is being performed in the field of developing new and more efficient hybrid vehicles. Biggest drawback is still posed by that of the power source being used in the vehicles, since it accounts for increasing most of the cost and the weight of the vehicle.

This report looks at the various types of hybrid electric vehicles based on their power train configuration, and on the power source arrangement, analyzing important factors that affect the selection of a particular type of battery to power the vehicle, and looking at different options for batteries available, and under development. An attempt is made to come up with a selection made on the basis of the characteristics, compared on the grounds determined, and selecting a battery type.

II. HYBRID ELECTRIC VEHICLES

Electric Vehicles (EVs) are the vehicles which involve electric propulsion [2-3]. EV can be classified into three types: pure electric vehicles (PEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs). They are in different stages of development due to the existing technology, the major characteristics and features of three types of EV's. Electric motor drive technique, in which the field-oriented control (FOC) and variable-voltage variable frequency (VVVF) are adapted widely, is the common technique in EV. The battery initial cost and battery management create bottleneck in PEVs in spite of zero emission; these two barriers cannot be solved in the near future, so the HEV is the interim solution before the full commercialization of PEV, when there is a breakthrough in battery initial cost and management. FCEV has long-term potential for future main stream vehicles [4-7], however the technology of its cost and refueling system is still in early development stage [4].

Types of HEV's by drive train:

A. Series Hybrid:

In a series hybrid system, the internal combustion engine (ICE) drives an electric generator (usually a three-phase alternator plus rectifier) instead of directly driving the wheels. The electric motor is the only means of providing power to the wheels. The generator both charges a battery and powers an electric motor that moves the vehicle. When large amounts of power are required, the motor draws electricity from both the batteries and the generator.

There are several advantages to using the series hybrid electric configuration, including no mechanical link between the combustion engine and the wheels so that the engine-generator group can be located everywhere. There are no conventional mechanical transmission elements (gearbox, transmission shafts). Separate electric wheel motors can be implemented easily. The combustion engine can operate in a narrow Rotations per Minute (rpm) range (its most efficient range), even as the car changes speed. Series hybrids are relatively the most efficient during stop-and-go city driving [8].

The total weight of the powertrain can be excessively high, and since there are many energy conversions taking place, before the power from the engine reaches the wheels, the overall efficiency of the entire system can decline significantly.

B. Parallel Hybrid

Parallel hybrid systems have both an ICE and an electric motor in parallel connected to a mechanical transmission.

This configuration offers an increase in the total efficiency during cruising and long-distance highway driving and a larger flexibility to switch between electric and ICE power. On the other hand, the rather complicated system and the internal combustion engine not operating in a narrow or constant RPM range provide a setback to using parallel hybrid configuration, vastly. Also, the battery cannot be charged separately, due to direct coupling of internal combustion engine to the wheels.

C. Combined Hybrid

Combined hybrid systems have features of both series and parallel hybrids. There is a double connection between the engine and the drive axle: mechanical and electrical. This split power path allows interconnecting mechanical and electrical power, at some cost in complexity.

Power-split devices are incorporated in the powertrain. The power to the wheels can be either mechanical or electrical or both. This is also the case in parallel hybrids. But the main principle behind the combined system is the decoupling of the power supplied by the engine from the power demanded by the driver.

Combined hybrid offer the advantage of providing the maximum flexibility to switch between electric and ICE power. Also, the decoupling of the power supplied by the engine from the power demanded by the driver allows for a smaller, lighter, and more efficient ICE design.

But this increased flexibility comes at a price of a very complicated and expensive system than the parallel hybrid system. Moreover, the efficiency of the power train transmission is dependent on the amount of power being transmitted over the electrical path, as multiple conversions, each with their own efficiency, lead to a lower efficiency of that path (~70%) compared with the purely mechanical path (98%) [8].

Types of HEV’s by degree of hybridization:

A. Strong or full hybrid

A full hybrid EV can run on just the engine, just the batteries, or a combination of both. A large, high- capacity battery pack is needed for battery-only operation. The ICE will be shut off when the electric motor is sufficient to provide the power [8].

B. Medium hybrid or motor assisted hybrid

Motor assist hybrids use the engine for primary power, with a torque-boosting electric motor connected in parallel to a largely conventional powertrain. EV mode is only possible for a very limited period of time, and this is not a standard mode. Compared to full hybrids, the amount of electrical power needed is smaller, thus the size of the battery system can be reduced. The electric motor, mounted between the engine and transmission, is essentially a very large starter motor, which operates not only when the engine needs to be turned over, but also when the driver "steps on the gas" and requires extra power. The electric motor may also be used to re-start the combustion engine, deriving the same benefits from shutting down the main engine at idle, while the enhanced battery system is used to power accessories. The electric motor is a generator during regenerative braking [8].

C. Mild hybrid / micro hybrid (start/stop systems with energy recuperation)

Mild hybrids are essentially conventional vehicles with oversized starter motors, allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restart quickly and cleanly. During restart, the larger motor is used to spin up the engine to operating rpm speeds before injecting any fuel.

As in other hybrid designs, the motor is used for regenerative braking to recapture energy. But there is no motor-assist, and no EV mode at all. Therefore, many people do not consider these to be hybrids, since there is no electric motor to drive the vehicle, and these vehicles do not achieve the fuel economy of real hybrid models [9].

D. Plug-in hybrid (grid connected hybrid)

PHEV is a full hybrid, able to run in electric-only mode, with larger batteries and the ability to recharge from the electric power grid. Their main benefit is that they can be gasoline-independent for daily commuting, but also have the extended range of a hybrid for long trips.

Grid connected hybrids can be designed as charge depleting: part of the “fuel” consumed during a drive is delivered by the utility, by preference at night. Fuel efficiency is then calculated based on actual fuel consumed by the ICE and its gasoline equivalent of the kWh of energy delivered by the utility during recharge. The "well-to-wheel" efficiency and emissions of PHEVs compared to gasoline hybrids depends on the energy sources used for the grid utility (coal, oil, natural gas, hydroelectric power, solar power, wind power, nuclear power) [8].

In a serial Plug-In hybrid, the ICE only serves for supplying the electrical power via a coupled generator in case of longer driving distances. Plug in hybrids can be made multi-fuel, with the electric power supplemented by diesel, biodiesel, or hydrogen [12-13].

For typical driving cycles, the achieved efficiencies are lower. The battery powered EV achieves efficiencies in the range of 50 to 60 percent. The hydrogen powered EV has a total efficiency of about 13 percent only at those drive cycles [8, 12-13].

III. Factors Affecting Selection of Power Source for a PHEV

A. Energy density and power density

Specific energy or gravimetric energy density defines the battery capacity in weight (Wh/kg); energy density or volumetric energy density is given in size (Wh/l). A battery can have a high specific energy but poor specific power (load capability), as is the case in an alkaline battery. Alternatively, a battery may have a low specific energy but can deliver high specific power, as is possible with the super capacitor. Specific energy is synonymous with battery capacity and runtime [10].

On the other hand, specific power or gravimetric power density indicates the loading capability, or the amount of current the battery can provide. Batteries for power tools exhibit high specific power but have reduced specific energy (capacity). Specific power is synonymous with low internal resistance and the delivery of power.

The electrical energy storage units must be sized so that they store sufficient energy (kWh) and provide adequate peak power (kW) for the vehicle to have a specified acceleration performance and the capability to meet appropriate driving cycles. For those vehicle designs intended to have significant all-electric range, the energy storage unit must store sufficient energy to satisfy the range requirement in real-world driving.

Typical energy requirements of hybrid vehicles [11]:

- Starter/ micro hybrid vehicles: 720 kWh
- Hybrid electric vehicles: 1500 kWh
- Plug-in HEVs: 12,500 kWh
- Full electric vehicles: 25,000 kWh

B. Operating range

Operating range defines the range to which a P-HEV can be used reliably before it needs to be recharged. Plug in hybrid electric vehicles can be designed to work up to various ranges of distances, some for short distances, like in the city (ranging from an assumed 30-100 km) and others, on the highways and expressways (ranging from an assumed 100-300 km).

C. Charge recharge cycles

The charge and discharge current of a battery is measured in C-rate. Most portable batteries, with the exception of the lead acid, are rated at 1C. A discharge of 1C draws a current equal to the rated capacity. For example, a battery rated at 1000mAh provides 1000mA for one hour if discharged at 1C rate. On charge, 1C charges a good battery in about one hour; 0.5C takes 2 hours and 0.1C 10 to 14 hours.

Thus the distinction between various types of batteries on the basis of charge-recharge cycles is vital to the process of selection of best battery type for PHEVs [14].

D. Cost

Different types of batteries vary in their price range for example, lead-acid batteries cost the minimum, whereas, the lithium-ion batteries, owing to their better technology, cost much higher than the former.

The cost of batteries has a direct impact over the price of the plug-in hybrid vehicles, since one of the most costly part of the vehicle is the battery itself.

IV. Energy Options Available

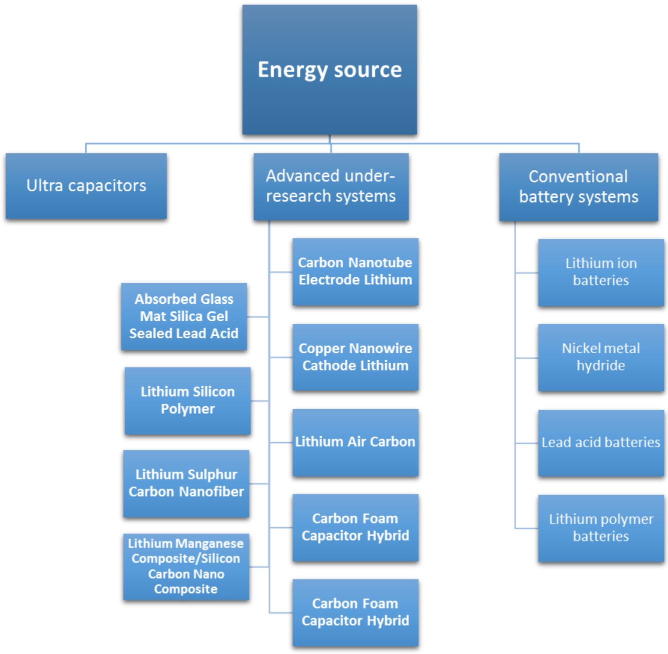

Fig. 1 Available options for power source for a PHEV

A. Carbon Nanotube Electrode Lithium

Carbon Nanotube Electrode Lithium consists of various layers of carbon nanotubes (strong microscopic hollow threads with relatively large area) developing a cathode (the electrode through which electrons flow out of a battery) that can store and release many more positive ions than a conventional lithium battery leading to increase in the amount of power stored in an electric car battery and increase in the electricity flow by as much as ten times compared to current products. This could also enhance solid-state capacitors but the technology is at least five years away [31].

B. Copper Nanowire Cathode Lithium

Copper Nanowire Cathode Lithium is obtained by replacing the porous and conductive graphite electrode with microscopically thin copper wires that can store ions on their entire surface instead of just on a flat metal surface copper itself is less susceptible to heat than other materials, and its ability to store ions is said to be greater than the graphite currently used in lithium batteries therefore, it can store and release much more power than conventional lithium batteries [15].

C. Lithium Air Carbon

Lithium air carbon technology consists of a metal-air battery chemistry that uses the oxidation of lithium at the anode and reduction of oxygen at the cathode to induce a current flow. Being an all-solid-state battery, it has a very high specific energy (11,140 (theoretical) W.h/kg) and an energy density (per kilogram) comparable to gasoline, but the technology still requires significant research in a variety of fields before a viable commercial implementation is available. The nominal cell voltage is about 2.91 V [16].

D. Carbon Foam Capacitor Hybrid

Carbon Foam Capacitor Hybrid basically combines the electrical storage density of a chemical battery and the power delivery efficiency of capacitors (solid state). A unique carbon foam is used as a cathode to increase storage capacity and carbon anode leads to less weight. This hybrid offers more charge than typical capacitor and more recharge cycles [17].

E. Lithium Silicon Polymer

It offers a lithium battery that can store increased levels of energy over those in today's cars. Unlike other designs that uses silicon electrodes, a specially constructed polymer maintains the structure of the electrodes while they expand and contract. This new kind of anode can absorb eight times the lithium of current designs [17].

F. Lithium Sulphur Carbon Nanofiber

Silicon's ability to store many more lithium ions than current electrodes makes it an attractive choice to increase power density in batteries. But Silicon expands significantly when it absorbs ions, and that movement tends to break the conductivity path of the anode. However, making nanofibers out of the silicon reduces this effect. The carbon nanotubes are coated on the inside with sulphur which allows their batteries to store up to ten times the energy of conventional lithium batteries. Sulphur is a more environmentally friendly (and cheaper) electrode coating, because it is readily available and non-toxic.

G. Lithium Manganese Composite/Silicon Carbon

Lithium Manganese Composite offers a cathode material based on manganese, an abundant metal that is stable when used in the battery. Manganese is also less expensive than the more common cobalt-based cathode material. Batteries made out of this material could give a range of 300 miles in an EV. The latest 12-volt batteries are sealed lead acid units called absorbed glass mat (AGM) batteries and the sulphuric acid electrolyte is contained in a fiberglass mat, and combined with a gel instead of liquid electrolyte which offer good cyclical use in boats as well as cars, since these lead-acid batteries hold a charge often up to a year and boast longer life than conventional AGM batteries without gel electrolyte. This new silica gel and glass matting that stays in contact with electrodes, as well as lead-calcium electrodes, has made these already-affordable batteries better [17].

V. CONVENTIONAL SYSTEMS

A. The lead acid batteries

The lead acid batteries have been in use for a long time, but for use in a PHEV, they offer low specific power (180 W/kg) and low specific energy (33-42 Wh/kg) however, the energy density provided is reasonable (60-110 Wh/l). Although they provide a reasonable cell voltage (2 V/cell), their poor cold temperature performance (min. −35 °C, max. 45 °C), less cycle durability (500–800 cycles) and short calendar life (easy wear out) prove to be a setback for their use in vehicles. Moreover, their life cycle impede by their use, giving a high self-discharge (3–20% per month). In spite of being relatively inexpensive, their charge/discharge efficiency is not too high (50–95%).

B. The nickel-metal hydride batteries

Nickel metal hydride batteries find common use in electronic devices already, because of the fact that they provide reasonable specific energy (60–120 Wh/kg), high energy density (140–300 Wh/L) and a higher specific power (250–1,000 W/kg). Although having low charge/discharge efficiency of approx. 66 percent and very low nominal cell voltage of 1.2 V, its high energy/consumer-price (2.75 Wh/US$) and higher cycle durability (500–2000 cycles) makes it a popular choice for small electronic devices running on low voltages. This small voltage is, however not acceptable to be used in a plug-in hybrid [18].

C. The lithium polymer batteries

Lithium polymer offers a specific energy of 100–265 W.h/kg (0.36–0.95 MJ/kg) and an energy density of 250–730 W.h/L (0.90–2.63 MJ/L) while offering a nominal cell voltage of 3.3 V to 3.7 V, depending on temperature. Their small form factor is an added advantage to be considered as an option for hybrid vehicles, although the high cost poses a disadvantage [19].

D. Lithium ion batteries

Offering a high specific energy of 100–265 Wh/kg (0.36–0.95 MJ/kg), high energy density of 250–620 Wh/L (0.90–2.23 MJ/L), a higher specific power of ~250- ~340 W/kg and a lower energy/consumer-price of 2.5 Wh/US$, lithium ion batteries provide good high temperature performance and low self-discharge, making them the best choice for PHEVs. Moreover, the components are recyclable and cycle durability is high (400-1200 cycles), producing about 120 kWh/kg of energy which, although higher than other types of batteries, is still less as compared to fossil fuel energy density (~12000 kWh/kg). The charge/discharge efficiency is almost 80–90% which is quite acceptable for use in hybrid vehicles. The self-discharge rate varies as 8% at 21 °C, 15% at 40 °C and 31% at 60 °C (per month). The nominal cell voltage delivered by Lithium-Nickel-Manganese-Cobalt (NMC) type lithium ion battery is 3.6/3.7 V, and that of $LiFePO_4$ is 3.2 V.

Based on the above facts, it is evident that the most suitable type of batteries for PHEV’s are the lithium ion batteries. On further study about lithium ion batteries, if was found that depending on the type of technology used in lithium ion batteries, the specifications of the batteries change significantly.These are discussed as below.

VI. LITHIUM-ION BATTERIES

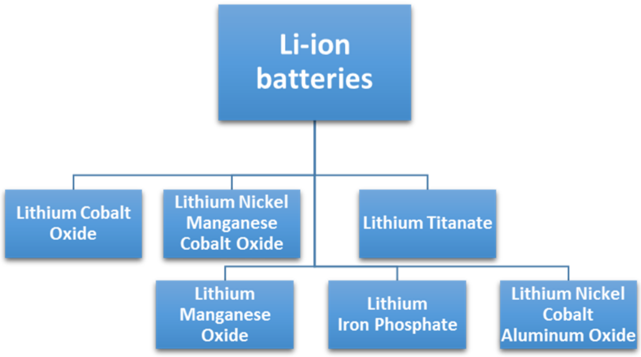

Fig. 2 Classification of Lithium-ion batteries on the basis of technology used[10].

A. *Lithium Cobalt Oxide ($LiCoO_2$)*

Lithium Cobalt Oxide ($LiCoO_2$) batteries offers high specific energy (1.1 kW h kg−1) and consists of a cobalt oxide cathode and a graphite carbon anode. The cathode has a layered structure and during discharge the lithium-ions move from the anode to cathodeThese batteries, however, cannot be charged and discharged at a current higher than its rating [20-21].

B. *Lithium Manganese Oxide ($LiMn2O_4$)*

Lithium Manganese Oxide ($LiMn2O_4$) are fast charging and high-current discharging batteries in which the architecture forms a three-dimensional spinel structure that improves ion flow on the electrode, which results in lower internal resistance and improves current handling. They can be discharged at currents of 20–30A with moderate heat build-up, however, cell temperature cannot exceed 80°C (176°F). Since they offer 50% more energy than nickel-based chemistries, and have design flexibilities, that allows engineers to maximize the battery for either optimal longevity (life span), maximum load current (specific power) or high capacity (specific energy) [21-22].

C. *Lithium Iron Phosphate ($LiFePO_4$)*

Lithium Iron Phosphate ($LiFePO_4$) offers good electrochemical performance with low resistance by using Nano-scale phosphate cathode material that provides enhanced safety, good thermal stability, high current rating and long cycle life, and is tolerant to abuse. The lower voltage of 3.3V/cell reduces the specific energy to slightly less than Li-manganese. Cold temperature, however reduces performance, and elevated storage temperature shortens the service life [21-24].

D. *Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)*

Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) systems can be tailored to high specific energy or high specific power, but not both. The cathode combination of one-third nickel, one-third manganese and one-third cobalt offers a unique blend that also lowers raw material cost due to reduced cobalt content [21-22].

E. *Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)*

Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$) offer high specific energy and power densities, and a longer life span. However, they have low safety and cost higher than the others, ruling out their candidacy for use in PHEVs [21-23].

F. *Lithium Titanate ($Li4Ti5O1_2$)*

Lithium Titanate ($Li4Ti5O1_2$) replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure, offering a nominal cell voltage of 2.40V and can be fast-charged. It delivers a high discharge current of 10C, or 10 times the rated capacity with a cycle count higher than that of a regular Li-ion. These systems are safe, has excellent low-temperature discharge characteristics and obtains a capacity of 80 percent at –30°C (–22°F). The specific energy offered, is, however, low (65Wh/kg) [21-22].

Table 1: Characteristic table of various Li-ion battery types [24]

Specifications	Li-cobalt $LiCoO_2$ (LCO)	Li-manganese $LiMn_2O_4$ (LMO)	Li-phosphate $LiFePO_4$ (LFP)	NMC $LiNiMnCoO_2$
Voltage	3.60V	3.80V	3.30V	3.60/3.70V
Charge limit	4.20V	4.20V	3.60V	4.20V
Cycle life	500–1,000	500–1,000	1,000–2,000	1,000–2,000
Operating temperature	Average	Average	Good	Good
Specific energy	150–190Wh/kg	100–135Wh/kg	90–120Wh/kg	140-180Wh/kg

Loading (C-Rate)	1C	10C, 40C pulse	35C continuous	10C
Safety	Average. Requires protection circuit and cell balancing of multi cell pack. Requirements for small formats with 1 or 2 cells can be relaxed		Very safe, needs cell balancing and V protection.	Safer than Li-cobalt. Needs cell balancing and protection.
Thermal runaway	150°C (302°F)	250°C (482°F)	270°C (518°F)	210°C (410°F)
Cost	Raw material high (cobalt)	Raw materials moderate	Manufacturing cost high	Raw materials moderate
In use since	1994	1996	1999	2003
Notes	Very high specific energy, limited power.	High power, good to high specific energy; EVs.	High power, average specific energy, safest lithium-based battery.	Very high specific energy, high power; tools

Conclusion

HEVs and their various configurations are studied and power requirements of PHEVs, including energy density, power density, cost, operating range etc. are identified.

Various types of battery systems available and being researched including nickel-metal-hydride batteries, lithium polymer batteries, and lithium ion batteries were studied theoretically, and based on the statistics, and the basis on which selection of batteries for a PHEV depends as stated above, the battery type most suitable to be used in a PHEV system is chosen. The battery that came out to be the most effective were Lithium-Nickel-Cobalt-Aluminium (NCA) and NMC type Li-ion batteries.

For vehicles that require high energy but low power, NMC batteries are identified as the better option and for vehicles that require high power but can make a compromise on the energy density, or the range of vehicle driven, the NCA Lithium-ion batteries was identified as a better option.

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