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Can Li-Ion batteries be the panacea for automotive applications?

A. Opitz[a], P. Badami[a,b], L. Shen[a], K. Vignarooban[a,c], A.M. Kannan[a,*]

[a] *The Polytechnic School, Ira A. Fulton Schools of Engineering, Arizona State University, Mesa, AZ 85212, USA*
[b] *School for Engineering of Matter, Transport and Energy, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ 85287, USA*
[c] *Department of Physics, Faculty of Science, University of Jaffna, Jaffna 40000, Sri Lanka*

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ABSTRACT

The fuel economy of 31 MPG (based on combined city and highway) and Environment labels are being affixed to new vehicles after 2013 model year, as mandated by the U.S. Environmental Protection Agency. Most of the fuel-efficient 2016 model year passenger cars are hybrid electric vehicles. Hybrids combine the best features of the internal combustion engine with an electric motor powered by batteries and can significantly improve fuel economy. Plug-in hybrids are plugged into wall outlet for battery recharging or driven by electric motor for relatively longer distance. The all-electric vehicles are propelled by electric motor powered using rechargeable battery packs, emitting no tailpipe pollutants. Among various battery technologies, Li-ion battery system is the more preferable one for the automotive applications due to their relatively higher energy density. This review examines various aspects of Li-ion batteries related to performance, durability, energy management and safety related to automotive applications. The review also discusses about the possibility of automotive Li-Ion batteries towards second life in stationary applications.

1. Introduction

There are many variants being offered in the vehicle market including micro hybrids, mild hybrids, plug-in hybrids (PHEVs) and all-electric vehicles (EVs) with battery systems. A micro hybrid vehicle is a system that has the start-stop technology. This allows the vehicle to be started by the battery pack, capture energy to be stored into the battery while braking, and the ability to support the electrical systems when the internal combustion engine (ICE) is shut off. The mild hybrid has same features as that of micro hybrid along with some additional features. These features are an electric motor/generator in parallel with the ICE, which can assist when the vehicle is coasting, braking or stopped. Although the mild hybrid can assist combustion engine, there is no electric-only mode of driving. PHEV has the same features of the mild hybrid vehicles with the ability to plug into the electrical grid as well as having an electric-only mode of driving. PHEV performance is strongly influenced by powertrain architecture and is classified into input split, parallel, series, series-output split and series-parallel. Series configuration has higher efficiency in EV mode, but lower efficiency in hybrid mode due to losses in electric motor and the parallel configuration has higher efficiency compared to series architecture due to lower losses in electric motor [1]. Fig. 1 shows the schematic of series and parallel hybrid powertrains. The series configuration consists of generator and motor and the traction is only provided through motor. Motor receives power either through battery pack or generator operated by ICE [2,3]. In the case of parallel architecture, traction is provided by ICE or battery pack in tandem arrangement while batteries are recharged through motor/generator during coasting and braking. An all-electric vehicle runs solely on the battery system powering the motor. The hybrid and electric vehicle markets are being driven by a number of factors such as consumer interest, technology, cost, regulatory requirements and a variety of government incentives. These factors are influenced by battery system characteristics such as cell chemistry, energy density, power density, cycle life as well as operating conditions.

The type of chemistry is extremely important as it dictates inherent safety, shelf life, battery design and so on. Among various battery systems, Pb-acid batteries are relatively less expensive among existing automotive battery systems, they use toxic materials and exhibit lowest energy density [4]. Ni-Cd batteries on the other hand show higher energy and power density values compared to Pb-acid batteries, but the electrode materials are toxic (Cd anode) and expensive. Although Ni-MH batteries are better compared to Ni-Cd batteries in terms of energy and power densities with environmentally friendly MH anode, the self-discharge is higher and require complex charging protocols. LIBs are relatively more expensive than other cell chemistries, but they provide the highest energy and power densities as well as longer cycle life and have the ability to incorporate smart battery management systems.

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* Corresponding author.
E-mail address: amk@asu.edu (A.M. Kannan).

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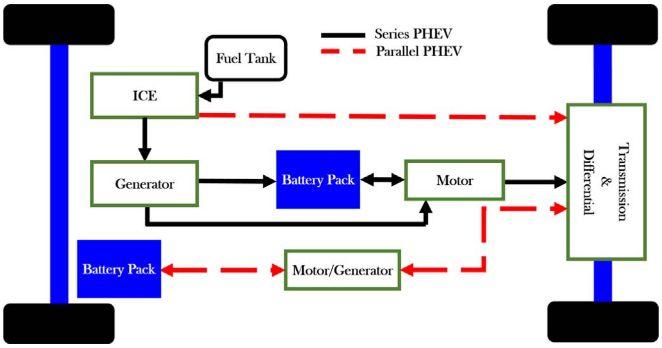

Fig. 1. Series and parallel plug-in hybrid powertrains.

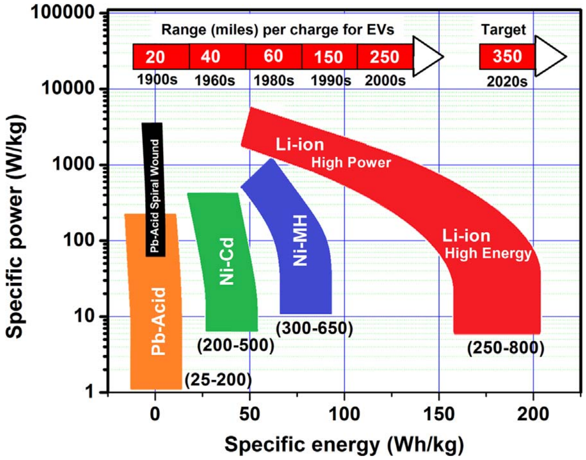

Fig. 2. Comparisons of various battery systems along with miles per charge and target. The numbers in parenthesis is the price (USD) for the particular battery system per kWh.

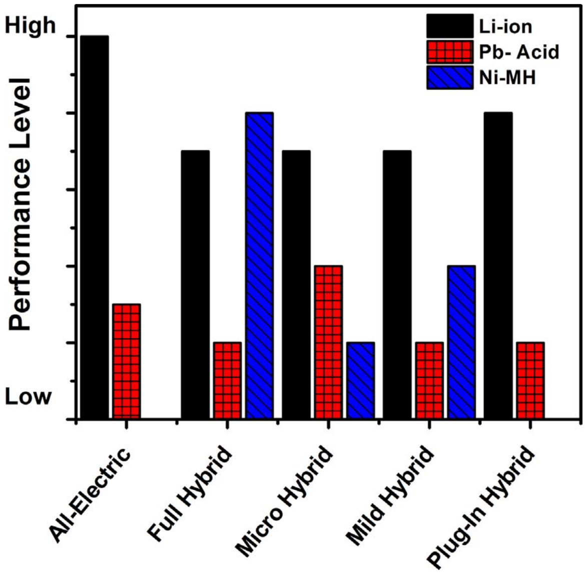

Fig. 3. Performance levels of different EVs using various battery systems.

Fig. 2 shows the specific energy dependence of specific power with the driving range (per charge) of different cell chemistries along with price range per kWh [4]. As indicated in Fig. 2, the driving range target would be 350 miles per charge by 2020 to take on the ICEs. LIBs perform relatively well in all the possible variants (Fig. 3) and the additional costs can be overlooked [4].

The major focus of this review is to bring out the salient features of LIBs based on performance, cycle life, safety aspects to assess if they can be a cure all for automotive applications. In addition, the possibility of using the retired automotive batteries for any stationary applications (second life) is also discussed.

2. Safety protocols

Safety has always been a paramount factor when developing and testing the battery system for consumer applications in automobiles. As of late, there are safety experiments being carried out by researchers, organizations, and automakers to ensure safety of battery systems, but there are no unified standards. There might not be standards for battery chemistry because organizations base their standards only on a particular battery chemistry or application. For this reason, there should be a priority to establish a unified standard for automotive batteries, so that the performance and safety could be improved. One possible solution to this problem could be creating an international agency or adding authority to an existing agency to regulate automotive batteries. Another possible solution is to have pre-existing organizations form into a council that governs over a collaborated set of regulations. Possible candidates for the council could be the Society of Automotive Engineers, European Norm and the ISO 9000 standards. Further debate should be conducted for the hypothetical structure of universal automotive standards.

The main safety tests that are being carried out on automotive batteries are analogous to stationary and portable batteries. These tests are most likely being done because regardless of the chemistry or application, batteries share a fundamental set of characteristics. The differences in battery evaluation only occur due to the application and battery chemistry in which diverse tolerances are allowed. In a recent publication on "*Are Lithium Ion Cells Intrinsically Safe?*" and also in another paper by the same group, the batteries have been evaluated for mining applications under harsh conditions similar to that an automotive battery could possibly experience [5,6]. The experiment had two set-ups with one using the UL Standard 1642 and the other being a modified version of the UL 1642 with a 90° plastic wedge. Additionally, the set-up has a controlled atmosphere with moderate level of methane in a temperature range 25–40 °C. The safety tests revealed that the A123 26650 (LiFePO$_4$) cell was a safer design compared to LG Chem ICR18650S2 (LiCoO$_2$). Results also demonstrated that LiFePO$_4$ can withstand physical abuse without causing any safety hazards, while LiCoO$_2$ generated instantaneous fire. As far as safety requirements are concerned, A123 26650 battery with LiFePO$_4$ cathode can be seen as a good choice for automotive applications.

Zaghib et al. [7] studied the safety and performance of the cylindrical battery chemistry of LiFePO$_4$, LiMn$_2$O$_4$, and LiNi$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$ to identify the best cell design. The batteries used in this experiment could be possible candidates for being used in EVs, because they could provide the possible performance needed for automotive applications. One part of the experiment was to test the capacity loss after cycling at low and high C-rates while observing the heat generation during charging and discharging of the batteries. Furthermore, a crush and nail penetration test was also done on all of the battery chemistries mentioned above to examine thermal runaway and, if any internal short-circuit was produced. It is interesting to note that LiFePO$_4$ provided outstanding safety and good electrochemical performances, while the other chemistries are relatively unsafe except LTO/LiCoO$_2$ (see Fig. 4). From an overall quality standpoint, it appears that LiFePO$_4$ cathode provides comparable characteristics as other lithium chemistries, and leads superior safety in hazardous situations. Hence, LiFePO$_4$ would most likely be the best choice in designing a battery pack for an automotive application. There are several studies on the design and safety of battery chemistries and how well they perform in extreme situations [2–5]. Experiments under real time operating conditions can be an important way to understand the failures of a battery system, but a real world situation may shed light on every type of battery failure that an experimental test could not find.

Recently, a Tesla model S reached an unfortunate accident in