Electric Vehicle Batteries: Li-ion and Beyond, Challenges and Advancements

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Batteries are key to developing affordable Electric Vehicle (EV). However, EVs have not yet come on par with gasoline vehicles in many areas such as price, driving range, and recharge time. Many research areas are actively seeking to improve the current market dominant lithium-ion batteries (LIBs) as well as find alternatives to LIBs. This review will look at current status of LIBs, a few alternatives, and collective challenges and advancements associated with these batteries.

Introduction

An electrochemical battery in an EV provides clean source of energy without Greenhouse gas (GHG) emission and noise pollution that is typical of internal combustion engine vehicles. Resurrection of modern days EVs was initiated by Toyota Motors by introducing Prius Hybrid in 1997 with the Nickel Metal Hydride battery. By 2000, Prius was an international success, and it has been the highest selling hybrid to date. In 2008, Tesla Motors Inc. introduced highway-capable Tesla Roadster with 200+ miles range. In subsequent years, major auto manufacturers such as Chevrolet, Nissan, BMW, Audi, Mercedes and others have introduced their own EVs in response to the growing consumer demand.

The powertrain, especially the battery, is the most important component of an EV, which determines several crucial factors such as mileage range, purchase cost, safety, and convenience of recharge. The battery for an EV is simply the combination of individual battery cells in parallel and/or series. For instance, Tesla Model S uses over 7000 of the readily available Panasonic 18650-type lithium-ion (Li-ion) cells, whereas Nissan Leaf uses 192 individual Li-ion cells designed by Automotive Energy Supply Corporation (AESC). To achieve commercial success for EVs, batteries should have a right balance between storage capacity, cost, lifetime, recharge time, and safety, and LIBs currently hold collective advantage over other alternatives. Consumers want affordable, practical driving range comparable to that of a gasoline vehicle, convenient to recharge, and safe to operate EVs. All these factors are essentially battery related, and thus battery research and development is a key component in determining the rapid growth and success of EV market.

Battery Chemistry

A battery cell is simply a chemical composition of two electrodes and an electrolyte. The choice of electrodes and electrolyte composition, along with the structural design of the cell determine the electrochemical performance, cost, and safety of a battery. For instance, lithium, being the lightest metal and the strongest reducing agent, is unsurprising the most popular choice for positive electrode composition (such as LiFePO4) to yield light-weight, high energy density batteries. While numerous researches are being carried around the globe for affordable, high density LIBs, alternatives such as Lithium-air (Li-air), Lithium Sulfur (Li-S), and Magnesium ion (Mg-ion) are also being explored in response to the increasing demand. This paper will look at current market dominant LIBs and a few potential beyond Li-ion (BLI) successors, in terms of both challenges and advancements. It will also review the cost, range/recharge time, and safety issues commonly associated with these types of batteries.

LIBs

The theoretical density of a LIB is around 400-600 Wh/kg, but the current practical density is around 120-250 Wh/kg (see Figure 1). Although the theoretical energy density is low compared to other cells, for all the practical purposes, LIBs are the leading market leader for EVs. The commercial booming and success of LIBs after the introduction of Sony LIBs by Sony Inc. provided 25 years of head start for LIBs Energy density for LIBs is increasing at a rate of 5-10% per year which has enabled the commercialization of EVs, but growing energy consumption demands better performing batteries. Modern LIBs have seen only three-fold increase in energy density since the first commercial versions sold by Sony in 1991. Battery researchers believe storage capacity for LIBs is heading towards a saturation limit, and only technological improvements can potentially improve energy density by weight by about 30%. If this is the case, then EVs with LIBs will never achieve mileage range on par with traditional gasoline vehicles. Regardless, research continues to seek ways to achieve LIBs with higher specific energy density of around 400+ Wh/kg (see Table 1).
As a result, researchers keep looking for high conductive efficient electrolytes, and the combination of suitable electrodes and electrolytes to avoid such problems, and achieve higher Coulombic efficiency.\textsuperscript{10} Promising results in research laboratories on this front have not turned into commercial successes.\textsuperscript{11} The results obtained under controlled environments rarely hold up while shifting to large commercial scale for various reasons such as cost, efficiency at large scales, safety issues, and replication of results. For instance, Envia Systems, a battery startup, made big headlines in 2012 claiming a high density EV battery that could deliver 400 Wh/kg, which was about twice what any other batteries could deliver at the time. However, attempts to replicate the results failed. Envia associated the 400 Wh/kg landmark fluke with faulty results created by a contaminant in a batch of electrodes from the suppliers.\textsuperscript{11}

Many experts and battery research veterans feel 400 Wh/kg will be impossible to achieve before the end of the decade given the historically slow incremental gain in energy storage density since 1991.\textsuperscript{8} Despite some setbacks on commercializing potential LIB breakthroughs, several research groups and major companies are still working to develop LIBs that can achieve this milestone in foreseeable future. Samsung SDI, the world’s largest LIB maker, has set a more modest goal of achieving 250+ Wh/kg by 2019.\textsuperscript{12} BioSolar Inc., in partnership with University of California, Santa Barbara (UCSB), is targeting to develop LIBs with 450 Wh/kg by 2016.\textsuperscript{13} Tesla Motors, with Panasonic, is building a LIB factory Gigafactory 1 in Nevada, to be operational by 2016, to develop batteries with specific energy density of around 350 Wh/kg.\textsuperscript{10}

Although LIBs have greatly assisted the commercialization of EVs, transportation industry demands higher battery performance to challenge the traditional gasoline vehicles dominated auto market. Next-generation BLI batteries those can outperform LIBs in every criteria are needed for global deployment of EVs. The problem, however, lies in the fact that the current battery Research and Development (R&D) largely focuses on trial and error approach rather than the fundamentals of electrochemistry. Envia’s failure suggests that a better understanding of battery electrochemistry is favored over going through numerous possible permutations of electrodes and electrolytes composition to achieve desired results. For instance, replacing graphite anode in LIBs with pure sliver of lithium anode will greatly increase the energy density, and also makes the cell lighter and smaller in size. But, this increase in density comes at the cost of safety, and not enough has been done to overcome the challenge. Pure Li anodes suffer from what is called dendritic growth. During the cycling process of a LIB, microscopic fibers of Li-ion (called dendrites) emerge from one anode and keeps growing continuously across the electrolyte solution, and eventually reaches the cathode. When current flows through this dendrite, it can cause internal short-circuit, leading to overheating of the battery, and in some cases fire.\textsuperscript{14} This problem remains a challenge for BLI battery chemistries such as Li-S and Li-air, and has yet to meet with success.

**Li-S**

Although research on Li-S rechargeable batteries was originally done in the 1960s, they did not survive past 100 cycles, and subsequent interest in Li-S battery research faded.\textsuperscript{15} More than 50 years later, laboratory results have hinted at Li-S battery as one of the potential successors to LIBs primarily because of its theoretically high specific energy density (2,600 Wh/kg) and relatively low cost.\textsuperscript{16} In a typical Li-ion cell, the layered graphite electrode occupies a lot of space as a host for lithium ions, whereas in Li-S batteries each lighter sulfur atom can host two lithium ions, allowing for higher storage density.\textsuperscript{17} A sliver of pure lithium metal is used to perform double duty as an anode and as a lithium ion supplier. The sliver shrinks as the battery discharges and reforms as it is charged (see Figure 2 and 3).\textsuperscript{16} These factors create the potential to develop Li-S batteries that are lighter, and have higher energy density. In an positive recent development, a team of researchers from the University of California Berkeley and Lawrence Berkeley National Laboratory was able to retain Coulombic efficiency of over 99.7% after 1500 cycles in Li-S cells ,and the team estimates that a commercial version of the battery should deliver around 500 Wh/kg if it goes into production.\textsuperscript{16}

![FIG. 1: LIB discharge mechanism.\textsuperscript{18}](Image)
Although Li-S batteries seem promising, they have their own challenges. Internal short circuit caused by the dendrite formation remains the most challenging problem. Similarly, reaction between Li and S, during charge/discharge cycles, creates several polysulfide compounds, which, when dissolved into the liquid electrolyte, can diffuse back and forth between electrodes, forming insoluble Li$_2$S (or Li$_2$S$_2$) on the surface of the Li metal electrode, resulting in lower Coulombic efficiency. This problem was addressed using nanofabrication that uses cathode material designed using nanotechnology (core-shell nanostructure comprising Li$_2$S nanospheres with an embedded graphene oxide (GO) sheet as a core material and a conformal carbon layer as a shell (Li$_2$S/GO@C cathode) to avoid this problem and achieve the 99.7% Coulombic efficiency.

Likewise, another research team is addressing the fundamentals of Li-S electrochemistry by looking at theoretical calculations and computational analysis to better understand the sulfur redox chemistry on the electrolyte/carbon interface by using Raman spectroscopy and density functional theory (DFT). This understanding of fundamental electrochemistry will help maximize the usage of sulfur atoms for higher energy density and cycle stability as the research continues, and commercialization awaits.

There are a few industrial companies standing by Li-S battery development. Oxis Energy in Abingdon, UK has been developing Li-S batteries for various applications, and is setting new ambitions for its Li-S batteries use in EVs. It claims to have achieved energy density of 300 Wh/kg in 2014, and aims to reach 400 Wh/kg by 2016, and 500 Wh/kg by 2019.22 Sion Power, an Arizona-based rechargeable battery manufacturer, has claimed it already developed 350 Wh/kg Li-S cells in 2004 and is planning to develop 600 Wh/kg Li-S cells in near foreseeable future.15 Sions Li-S battery was used in Airbus Defense and Space Zephyr 7 prototype High Altitude Pseudo-Satellite (HAPS) aircraft in 2014, and the company is planning on releasing a commercial version of the battery for EVs before the end of decade.15

**Li-Air**

Li-air battery has also drawn research interest in past few years because of its high theoretical energy density (≈ 12,000 Wh/kg) and practical energy density (≈ 1,700 Wh/kg), which is comparable to that of gasoline.23 A Li-air cell uses the electrochemistry of oxidation of lithium at the anode and reduction of oxygen at the cathode (see Figure 4). A commercial version would potentially be lighter since it uses oxygen as cathode, and also cheaper compared to other conventional batteries.23

Research on Li-air Batteries, however, is still at an infancy state and continues to face many hurdles, mainly overvoltage and safety issues. Since the absorption and release of oxygen both happens at the cathode surface, a very large surface is required for higher energy density. Therefore, even though a Li-air cell has very high energy density, it has relatively low power density compared to the other existing batteries model. In addition, the lithium oxides formed during the reaction covers up the surface of the cathode resulting in poor Coulombic efficiency (around 60-70%). Li-air cell also exhibits large overvoltages (the charging voltage is considerably higher than the discharge voltage). As a consequence, the cell demonstrates poor cyclability. Current Li-air cells can undergo around 50 cycles before significant loss in storage capacity starts occurring. Li-air cells also suffer from the dendrite formation. Reactant product lithium peroxide (Li$_2$O$_2$, a strong oxidizer), combined with the electrolytes possesses safety risks during accidents. In addition, laboratory research uses pure oxygen, while the commercial batteries in cars would have to work in air which possesses several other challenges such as the reaction of lithium metal with nitrogen, carbon dioxide, and other gases present in air.
Decrease in cell storage capacity over time, volatility of electrolytes, and suitable porous membrane for the easy inflow of air while still keeping intact the electrolytes etc. are few other challenges hindering the commercialization of Li-air batteries.\textsuperscript{23,25,26}

IBM, in 2009, started Battery 500 Project to develop lighter, cheaper Li-air batteries with ten times the energy density than conventional LIBs that could deliver 500+ miles range on a single charge. In 2012, the Joint Center for Energy Storage Research (JCESR) at Argonne National Laboratory won US $120 million from the US Department of Energy (DoE). JCESRs target was to achieve an EV battery five times energy dense, and five times cheaper than any other currently available batteries. Although Li-air was considered by JCESR to have potential for being LIB successor, slow progress and safety issues of Li-air have refocused their priorities. For instance, efforts to eradicate the persistent dendrite problem with Li-air that cause short circuits and react aggressively with many other contaminants was only met with limited improvements. A research group in 2015 reported success with the preventive measure for dendritic growth in laboratory tests where it found that in situ formed nanostructure-stabilized solid electrolyte interphase (SEI) layers formed from the reactions between Li metal and solvents could prevent dendritic growth.\textsuperscript{27}

Despite the potential risks, major companies are standing by the potentials of Li-air battery. Volkswagen is planning on using Li-air batteries on its EVs within the next decade.\textsuperscript{28} Despite the initial setback, IBM is still planning to put Li-air battery on EV before 2020.\textsuperscript{29} Similarly, Samsung Inc. is also planning on bringing 300 Wh/kg Li-air in market by 2020.\textsuperscript{12}

Mg-ion

Another promising alternative for high density rechargeable batteries avoids lithium ion completely and uses heavier elements such as magnesium. Multivalent ions such as Mg-ions provide two electrons for current flow in contrast to just one from Li-ions.\textsuperscript{30} A Mg-ion battery can, thus, theoretically provide twice the current compared to a LIB under similar circumstances, which leads to theoretical energy density of around 800 Wh/kg.\textsuperscript{30} It also is cheaper and safer than a LIB.\textsuperscript{30} However, Mg-ions move very slowly through the electrolyte because of the heavy mass leading to lower Coulombic efficiency and greater charge/discharge time. A group of researchers from JCESR found that the Mg-ions were experiencing heavy drag because they were attracting other ions from the solvents (coordination spheres), and thus making them bulkier. Another JCESR research group through computational simulation suggested that the performance bottlenecks in Mg-ion batteries may be related to what happens at the interface between the electrolyte and electrodes as the Mg-ions shed their coordination spheres.\textsuperscript{31} Stable, high conductive, and non-corrosive magnesium battery compatible electrolytes for better flow of Mg-ions and longer cell life are also being explored. For instance, research group at Lawrence Berkeley is using supercomputer simulation of hundreds of different electrolytes to find the suitable combination of electrodes and electrolytes that offers least drag to mg-ions.\textsuperscript{8} In addition, major electronics firms and automakers such as LG, Samsung, Hitachi, and Toyota are also working on Mg-ion batteries.\textsuperscript{8}

While LIBs and BLI batteries are being explored, the common denominators that determine commercial success are cost, quick rechargeability, and safety. Consumers need to be convinced that EVs can perform on par with the gasoline vehicles, and thus, these three factors are crucial for any battery chemistry and research should be carried in parallel to optimize these factors.

Cost

Battery price is primarily responsible for the higher upfront price of an EV.\textsuperscript{4} Since most EV batteries are built by combining numerous individual cells, the battery price is determined largely by the cost of an individual cell. Comparing all factors, cathode materials, separators, and electrolytes have been the primary drivers of cost, and ongoing research is actively working to develop cheaper alternatives to existing materials.\textsuperscript{32} In addition to the individual cell cost, packaging cost, safety features, mass production, and business strategies are also responsible for driving higher prices for batteries. However, as one looks at the past decade, cost ($/Kilowatt-hour) has been significantly reduced, even faster than anticipated, especially for market dominant LIBs (Figure 5). The current price is still not low enough though to make EVs serious competitors in terms of upfront purchase cost.

![FIG. 4: $/KWh over the years.\textsuperscript{33}](Image)\textsuperscript{33}

In their research paper Rapidly Falling Costs of Battery Packs for Electric Vehicles authors Björn & Mån's looked at over 80 different sources between 2007-2014 to get an approximation on the $/KWh for successive years. They found that the cost declined by around 14%
annually, and the reduction had been largely due to reduction of materials cost, mass volume production, and engineering feats. Cost went down between 6-9% for cumulative doubling of production as a result of increase in EV sales. The price fell from around $1,000/KWh to around $400/KWh on average, while market leaders such as Nissan Leaf and Tesla Models S batteries are estimated around $300/KWh.\textsuperscript{33} In their research paper Rapidly Falling Costs of Battery Packs for Electric Vehicles authors Björn & Måns looked at over 80 different sources between 2007-2014 to get an approximation on the $/KWh for successive years. They found that the cost declined by around 14% annually, and the reduction had been largely due to reduction of materials cost, mass volume production, and engineering feats. Cost went down between 6-9% for cumulative doubling of production as a result of increase in EV sales. The price fell from around $1,000/KWh to around $400/KWh on average, while market leaders such as Nissan Leaf and Tesla Models S batteries are estimated around $300/KWh.\textsuperscript{33}

Industrial experts believe that the cost per kilowatt hour should be around $100/KWh-$150/KWh for a battery in order for an EV to be cost-competitive on par with a gasoline car.\textsuperscript{34} The fact that the practical limit of energy density used in current LIBs has not increased considerably means that price still hovers around $400/KWh on average.\textsuperscript{34} LIBs have room to improve, and possible alternatives have the capacity to deliver better $/KWh needed for commercial success. Although many laboratories results highlight several ways to achieve higher energy density with reduced cost, they often fail to hold on commercial scale.\textsuperscript{11} Nevertheless, mass production, cooperate strategy, and incremental engineering improvements in batteries have brought cost relatively down in past few years. It is most evident in case of Tesla Motors, which probably has the best $/KWh numbers in business.\textsuperscript{35} It has managed to increase energy density by more than 50%, and cut the price almost in half since its first launch of Tesla Roadster in 2008.\textsuperscript{35} Tesla Model S battery delivers 250 Wh/kg compared to around 100-200 Wh/kg for most others EVs on the market for a cost of under $300/KWh, and this cost reduction has not been due to radical improvement in LIB chemistry, but has come through engineering improvements such as battery packaging design, battery integration in vehicle, and cost effective safety materials.\textsuperscript{35}

\textbf{DoEs role in falling price}

Realizing the future potential of EVs, DoE has invested in funding to the development of better and cheaper batteries. DoEs Vehicle Technologies Office (VTO) partnered with United States Automotive Battery Consortium (USBAC) in 1991 to support the technological advancements of EV batteries. DoE invested around $315 million during 1992 - 2010 in R&D of affordable commercial batteries, especially LIBs during the later years.\textsuperscript{36} As a result of the collaboration, DoE claims that three US-ABC battery developers were able to increase the energy density by 60%, and reduce cost by 70% from around $1,000/KWh in 2008 to current cost of $289/KWh as of now.\textsuperscript{37} In 2009, DoE announced $2.4 billion in grants to several projects under the American Recovery and Reinvestment Act of 2009(ARRA) to accelerate the development of EV batteries and put the U.S. in the forefront of emerging EV market. In 2012, President Obama launched EV Everywhere Challenges as a part of Clean Energy Grand Challenges to offer affordable EVs to consumers with a decade. Argonne National Laboratory (ANL), National Renewable Energy Laboratory (NREL), and USABC are few big partners helping DoE achieve its target.

\textbf{Mileage and Charging Rate}

Most EVs still offer less than 100 miles range on a full charge, which is a discouraging factor for owners and potential buyers who are frequent travelers and long distance commuters. In addition to lower range, the recharge time is not all that impressive as well, and most of the EVs take well over hours (5+ hours - overnight) for full recharge.\textsuperscript{38} Range-anxiety (the fear that an EV will run out of power before reaching the next available charging station, and thus, leaving the vehicles occupant stranded) of owners and potential buyers can be eased with the development of quick recharging batteries with longer range.

Charging time vary depending upon the battery type, battery capacity, battery depletion amount, types of charger, external temperature, and several other factors.\textsuperscript{39} When an external charging source is connected to the battery pack, the reversal of electrons and ions flow takes place until the desired electric potential of the battery is restored. On cellular level, the unwanted results of electrochemistry such as drag force on ions, heat generation, and compounds deposition on electrodes decrease the Coulombic efficiency and increase the recharge time. The charge/discharge rate is thus largely determined by the chemical composition of electrodes and electrolytes, electrodes geometry, porosity of the electrodes and surface layer coating (see Figure 6). On the engineering side, nanoengineered electrodes with high porosity and the high surface area means greater number of ions flow, and faster recharge time.

Amongst all, the most limiting case for recharge process is the intercalation of ions into electrodes where the ions have to overcome an energy barrier at anode.\textsuperscript{40} Typical LIB electrodes (e.g. graphite anode and LiCoO\textsubscript{2} cathode) exhibit low diffusion rate of Li-ions compared to lithium salt electrolytes (e.g. LiPF\textsubscript{6}), leading to slow recharge.\textsuperscript{40} On the other hand, cycle-induced and time related factors such as consumptions of ions by SEI, polarization resistance, high voltage saturation etc. lead to capacity loss, lower coulombic efficiency, and longer
recharge times. For researchers wanting to cut down the recharge time, the focus has been on using the engineered nanostructures of electrodes (electrode nanoarchitecture) such as uses of inverse opal geometry for anodes (to achieve higher surface area, and thus higher diffusion rate and higher intercalation of Li-ions), and suitable chemical composition of electrodes and electrolytes for easy transportation of ions.

Since charge/discharge process is regulated by the intercalation of Li-ions in anodes, anodes with higher intercalation rate, and increased diffusion rate are being looked at through experiments and simulations such as Molecular Dynamics (MD) and Monte Carlo (MC). For instance, researchers simulated the charging process of LIB and found that applying oscillating voltage reduced the intercalation time of Li-ions into graphite anodes, and increased the diffusion of Li-ions into electrolytes, significantly decreasing the recharge time. Similarly, modern day nanofabrication techniques to develop high capacity anodes are also being researched, especially silicon since it has higher specific capacity (3580 mAh/g) compared to traditional graphite anodes (372 mAh/g). However, Si has relatively low conductivity, and also suffers from pulverization due to continuous expansion and contraction during the intercalation and deintercalation process, resulting in capacity reduction. To get rid of pulverization problem, high strength porous Si-based anodes could be nanostructured that could support the volume expansion of Si. Such methods include developing electrochemically grown 3D porous inverse opal structure of Si@Ni (Si electrodeposited into Ni scaffold allowing Si volume expansion with reduced stress, and also higher diffusion rate and better conductivity), and nanoengineered porous carbon black (CB) cage with conducting CB networks (Figure 6) that encapsulates Si (while CB cage reduces the stress on Si and provides expansion volume while maximizing surface area at the same time, CB networks enhance the electrical conductivity). At the same time, stable, non-corrosive, high conductive electrolytes those can increase intercalation rate are also crucial for fast recharge. For instance, high concentration of lithium salt (LiN(SO2F)2) in 1,2-dimethoxyethane (DME) ether solvent was found to result in even faster intercalation rate of Li-ions into graphite anodes compared to the commercially used ethylene carbonate electrolytes. As usual, these are all the laboratory successes results, and commercialization awaits.

Safety

All batteries should pass the governmental safety regulations before they could be put out in EVs and brought to market. Safety issues come in variety of forms from internal electrochemical safety failures to external abuses. The most recent headlining news would be the two Boeing 787 Dreamliner Li-ion batteries that caught fire, one in air in Japan, and other on ground in Boston. For the latter one, National Transportation Safety Board (NSTB) found a short circuit in one of the cells to be the most likely cause. Few other safety incidents that have caught public attention in recent years are battery ignition after crashes in Model S, battery pack ignition at assembly plant of Mitsubishi i-MiEV, and short circuit in battery pack of BYD e6 after crash. Few common safety concerns commonly associated with all types of battery chemistries are discussed below.

Electrical and Thermal Failures

As discussed before, dendrite formation is one of the major safety issues with Li-air and Li-S batteries. Dendrites cause internal short circuits, leading to overheating and, at times, ignition. Similarly, overcharge, overdischarge, overcurrent flow, low temperature charging (below 0°C) all generate unwanted exothermic reactions resulting in temperature rise (which might overcome the cooling efficiency of the battery), thus leading to overheating and potentially, ignition. This process, in addition to heat from internal resistance, might trigger series of uncontrolled electrochemical reactions, eventually leading to what is called thermal runaway, which might even lead to rupturing of battery. Laboratory research has shown promise in solving the short circuit problem. The use of nano-engineered anode materials is one method to avoid the dendrite formation. Another
method involves including temperature-responsive micro-capsules that can be embedded internally in LIBs, which will self-extinguish the fire if ignition occurs. Similarly, using biphenyl as polymerizable electrolyte additive can help protect the batteries from overcharge.

Mechanical Failures

Factors such as vibration, crush and penetration might lead to potential dangers of chemical exposure, thermal runaway, electric arcing, and fire ignition in batteries. Even if no safety risks occur, battery performance could drastically reduce due to the damage of components. Safety requirements for hazard prevention against mechanical abuse should include prevention of electrodes disintegration due to volume changes during cycling process, breakage of electrodes under shock, integrity of cells connectors, and prevention of electrolyte leakage. Battery penetration by sharp objects during crashes should be avoided by adding protective layers of materials. For instance, in 2014, Tesla Motors added additional protective layers to its battery pack with aluminum and titanium plates to deflect and/or absorb debris from the road during high-speed impact after a Model S vehicles caught fire upon hitting the debris on road. Since mechanical deformation can potentially lead to short circuit, computational and experimental research on the dynamic behavior of batteries upon crashing should be done to understand the mechanical properties of batteries depending upon the size, shape, packing design, shield materials strength, and shock absorption coefficient. Similarly, use of thermoresistant electrolyte that can perform under mechanically deformed batteries without short circuit, such as nanoarchitected Plastic Crystal Polymer Electrolytes (N-PCPE) could avoid hazard in the unfortunate events of collisions.

Conclusion

At present time when environmental pollution, global warming, and fossil fuel independence are making headlines, EVs are catching global attention as potential replacer of conventional gasoline vehicles. LIBs greatly assisted in the modern resurrection of EVs. Twenty five years of head start has made LIBs commercially dominant batteries in EVs. However, practical density of LIBs reaching towards saturation, and the increasing performance demand for EVs call for BLI alternatives. Potential successors of LIBs which hold high energy density such as Li-S, Li-air, and Mg-ions batteries are at the forefront of next-generation batteries research. These alternatives have their own challenges to overcome, and require optimization of storage capacity, cost, quick rechargeability, and safety to become commercial successes, and make EVs get on par with gasoline vehicles in foreseeable future. As of today, batteries remain the most important and challenging component for EVs. High energy density and low cost has been the holy grail of battery research. Researches are making gradual improvements in battery performance by incorporating the interdisciplinary branches of physics, chemistry, computational science, and engineering, evidenced by the increasing density, falling cost, and safer batteries. Although commercialization of many encouraging results from laboratory successes awaits to advance the current state of batteries, the future surely looks bright for EV market as indicated by the gradual improvement of battery technology. The success or failure of an EV hinges upon its battery performance. And much has yet to be done to make EV market a global success to which battery performance is quintessential.

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