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State-of-the-Art and Energy Management System of Lithium-Ion Batteries in Electric Vehicle Applications: Issues and Recommendations

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ABSTRACT A variety of rechargeable batteries are now available in world markets for powering electric vehicles (EVs). The lithium-ion (Li-ion) battery is considered the best among all battery types and cells because of its superior characteristics and performance. The positive environmental impacts and recycling potential of lithium batteries have influenced the development of new research for improving Li-ion battery technologies. However, the cost reduction, safe operation, and mitigation of negative ecological impacts are now a common concern for advancement. This paper provides a comprehensive study on the state of the art of Li-ion batteries including the fundamentals, structures, and overall performance evaluations of different types of lithium batteries. A study on a battery management system for Li-ion battery storage in EV applications is demonstrated, which includes a cell condition monitoring, charge, and discharge control, states estimation, protection and equalization, temperature control and heat management, battery fault diagnosis, and assessment aimed at enhancing the overall performance of the system. It is observed that the Li-ion batteries are becoming very popular in vehicle applications due to price reductions and lightweight with high power density. However, the management of the charging and discharging processes, CO2 and greenhouse gases emissions, health effects, and recycling and refurbishing processes have still not been resolved satisfactorily. Consequently, this review focuses on the many factors, challenges, and problems and provides recommendations for sustainable battery manufacturing for future EVs. This review will hopefully lead to increasing efforts toward the development of an advanced Li-ion battery in terms of economics, longevity, specific power, energy density, safety, and performance in vehicle applications.

INDEX TERMS Lithium-ion battery, state-of-the-art of lithium-ion battery, energy management system, electric vehicle.

I. INTRODUCTION

Currently, the green environment and environmental pollution risks are the most important concern of researchers. The internal combustion engine (ICE) based vehicles, factories and industries cause environmental pollution and global warming due to enormous emission of carbon gases. Environment researchers are keeping attention to develop electric vehicle (EV) have attracted more and more attention from environmental researchers [1], [2] because EVs use electrical energy to efficiently operate motors. A basic battery-powered electric vehicle system is shown in Fig. 1 where a differential, a mechanical transmission system, an electric motor, a power converter, a battery management system (BMS) and a battery pack are incorporated. The EV technology exhibits bidirectional energy flow at the time of running and braking [3].

Generally, electric vehicles can be classified according to the power source as follows: solely hybrid electric vehicles (HEVs), battery-powered electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), photovoltaic electric vehicles (PEVs) and fuel cell vehicles (FCVs) [4].

Li-ion batteries have a potential world market compared to other batteries in various applications due to their

FIGURE 1. Structure of the electric vehicle.

superior characteristics and advanced technology with the highest energy density, negligible memory effect and low self-discharge rate [5], [6]. Li-ion batteries are commonly applied in EVs and other systems as the primary or secondary energy source [7]–[9]. However, it requires the protection during charging and discharging. Because of the above attributes, including the low price, Li-ion batteries will face substantial future demand for aerospace and automotive applications [10]. EV systems might face trouble due to exceeding the current, voltage, or power limits as the battery cells could enter a thermal runaway state [11]–[13].

Currently, the Li-ion battery has become a more significant subject in power battery research and development and its application in EVs. [14], [15]. More importantly, due to use of graphic carbon as anodes, many various materials exist that can be used as cathodes of Li-ion batteries; thus the study and evaluations of various Li-ion battery types depending on the cathode materials is elaborated [16], [17].

Most of the researchers throughout the world are now concentrating on developing and modifying the lithium ion chemistry to achieve better performance considering the costs and other physical effects. The challenges for the management of battery charging and discharging within the ideal operating range of SOC have become more important topics for advanced research and technology. Now, the advancement of Li-ion battery production and application is growing beyond expectation. Fig. 2 shows the volume of research publications, specifically in engineering and physics research areas, on Li-ion battery technology and applications from the *Web of Science* database over the last decade [18]. The research has progressed dramatically throughout the world, though it was limited to a few Asian countries such as Japan, South Korea and China. Moreover, the research publications forecasted that the importance of Li-ion battery has been increasing over the years, as shown in Fig. 2 (b).

Conversely, as seen in Fig. 3, the manufacture of Li-ion batteries for vehicle applications is not common everywhere due to the necessary high technical support, management of raw resources and budget constraints [19], [20]. However, the governments of the most economically developed countries are concentrating on investing in installing battery industries because it is now possible to portably power vehicles without causing damages to the ecological systems. In this paper, the advantages and disadvantages of the most commonly used battery models are reviewed. In addition, a comparison study in the application of vehicles and current challenges and issues regarding Li-ion battery production

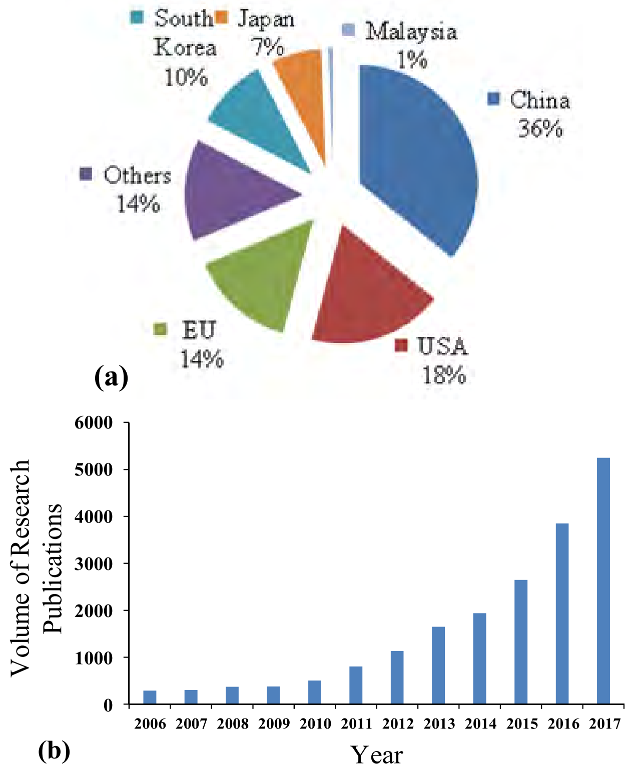

FIGURE 2. Volume of research publications on Li-ion battery technology and application: (a) country-wise, (b) in each year worldwide.

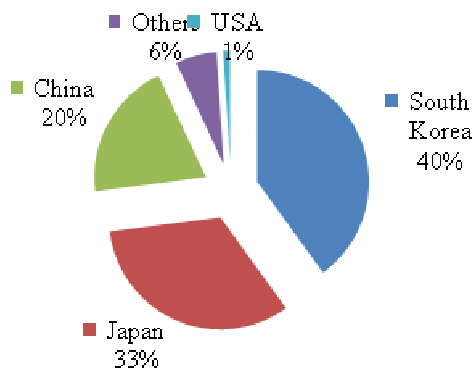

FIGURE 3. Manufacture of Li-ion batteries for vehicle applications and market share.

and action management with some recommendations are presented.

This paper contributes to the literature by reviewing the state-of-the-art of Li-ion batteries in EV systems and discussing the overview, characteristics, formations, types, performances and application of the Li-ion battery. This review covers an evaluation of Li-ion batteries and a comparison of the Li-ion battery with other common batteries. The features and functions of the Li-ion battery management system are explained along with the anticipated future development of sustainable EV energy storage technologies. This study also discusses and highlights the current issues and challenges of the production, protection, recycling and refurbishing of the Li-ion battery and makes significant recommendations for future development.

II. OVERVIEW ON LITHIUM-ION BATTERY

At the end of the 1900s, the battery was the only source of power because the power generator and grid supplies had not yet been invented. With the continuous development in this technology, many different types of batteries have been developed [20]. The "wet cells" were very common and used contained liquid electrolytes and metallic electrodes in an open container. This type of battery was reused by substituting the materials. Because they were not portable, early EVs utilized semi-sealed wet cells.

In the early age of battery technology, the current was produced as the assembled battery; however, this battery could not be recharged electrically when the active elements were depleted. There was a remarkable breakthrough when the lead-acid battery was invented with rechargeable types that could recharge the electric energy. It could store energy repeatedly and increase its lifetime. On the contrary, the Li-ion disposable battery has become increasingly popular in the rechargeable battery market because of its high energy density and long life although the price per unit is high. The methodologies and relationships among the volume of the battery and the energy density of the battery is given in equation (1), and the device longevity was investigated in [21].

$$\text{Volume of Battery} = \frac{(\text{Regulated Average Power})\ (\text{Device Longevity})}{\text{Energy Density of Battery}} \quad (1)$$

Li-ion batteries consist of two electrodes as the anode and the cathode, which are separated by a separator with an electrolyte where lithium ions move from the cathode to the anode during charging and where they move back during discharging, as illustrated in Fig. 4. Compared to non-rechargeable batteries containing metallic lithium, Li-ion batteries utilize a compound lithium electrode material [22]. They are now mostly available in consumer electronic products worldwide [23].

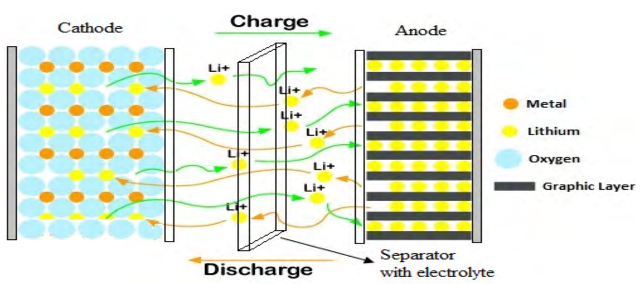

FIGURE 4. Charging and discharging phenomenon of Li-ion battery.

Instead of the lead-acid battery having heavy lead plates and an acid electrolyte, Li-ion batteries has become more commonly used as a portable rechargeable battery because they have high energy density and are lightweight in EV applications without any change in its drive system [24], [25]. Although Li-ion batteries have the best properties, they need high test conditions and protection during manufacturing and use due to the flammable electrolyte to avoid accident and failure [26], [27].

A. CHARACTERISTICS OF LITHIUM-ION BATTERIES

The important characteristics of Li-ion batteries include their size (physical and energy density), longevity (capacity and life cycles), charge and discharge characteristics, cost, performance in a wider temperature range, self-discharge profile and leakage, gassing, and toxicity impact [28]. In general, lithium ion batteries have positive and negative traits. The positive traits include their high specific energy (230 Wh/kg) and power density (12 kW/kg), good energy density, excellent cycle life and long life, and good charging and discharging efficiency. The cost, the electronic protection system that is mandatory during charging and discharging and the GHGs emissions during manufacturing and disposal are common negative points [29], [30].

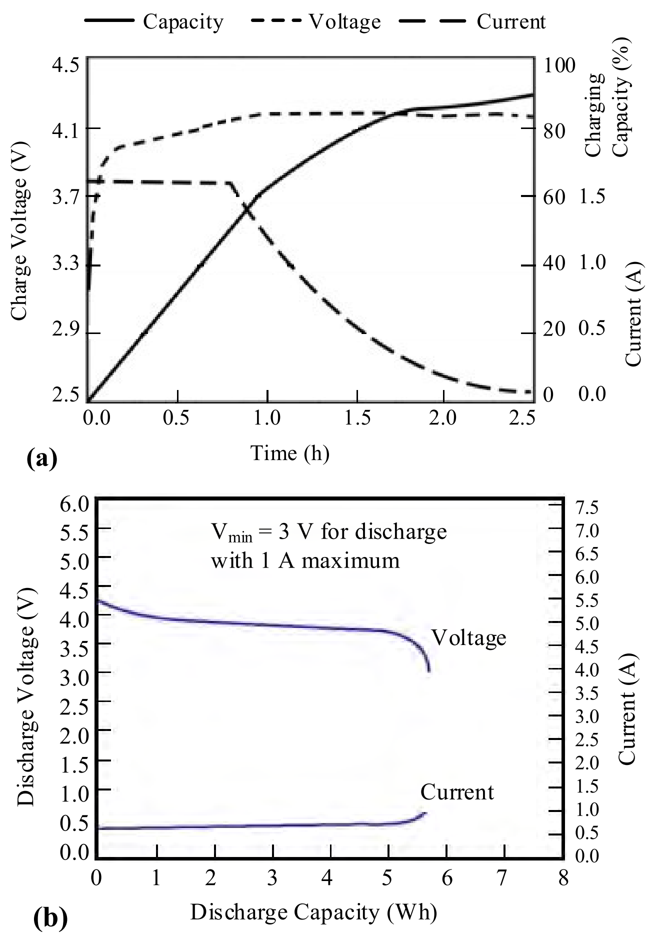

FIGURE 5. Typical characteristics of the lithium-ion battery (a) charging, (b) discharging.

The Li-ion battery has good charging and discharging electrical characteristics, as shown in Fig. 5. While charging, the charging capacity increases gradually with the charge voltage maintaining a constant current. When the voltage reaches a maximum, the current decreases exponentially. On the other hand, the capacity discharge maintains an almost constant voltage and current to the load, although there is a small decrease and increase in the voltage and current values, respectively, until the cell capacity reaches the minimum acceptable level, which is set by the manufacturer as an end-of-charge voltage.

B. LITHIUM-ION COMPONENTS

The Li-ion battery is composed of four primary components including the cathode, anode, electrolyte and separator, as shown in Fig. 4. The cathode is a lithium-metal-oxide powder. The lithium ions enter the cathode when the battery discharges and leave when the battery charges. The reactions below show the chemistry functions in moles. The chemical reaction of the cathode in [31] is shown as follows.

$$\mathrm{LiMO_2} \leftrightharpoons \mathrm{Li_{1-x}MO_2} + \mathrm{xLi^+} + \mathrm{xe^-}$$

The anode is a graphitic carbon powder. The lithium ions leave the anode when the battery discharges and enter the anode when the battery charges. The cathode reaction is given in [32].

$$\mathrm{C} + \mathrm{Li^+} + \mathrm{xe^-} \leftrightharpoons \mathrm{Li_xC}$$

The cathode and anode materials are made of lithium metal oxide and lithiated graphite in Li-ion batteries where both structures are organized in layer on aluminium and copper current collectors, respectively [33].

The electrolyte is composed of lithium salts and organic solvents; the electrolyte allows for the transport of the lithium ions between the cathode and anode rather than electrons. The separator is a micro-porous membrane that is used to rule out the short circuit between the cathode and anode and that only allows lithium ions to pass through the pores. The overall reaction of the lithium battery is given in [34] as follows.

$$\mathrm{LiMO_2} + C \leftrightharpoons \mathrm{Li_xC} + \mathrm{Li_{1\text{-}X}MO_2}$$

C. LITHIUM-ION BATTERIES FORMATIONS

Li-ion batteries can be constructed and packed in two major formations, which are metal cans either in cylindrical or prismatic shapes or laminate films (stacked cells) that are familiarized as Li-ion polymer batteries. Li-ion batteries can be shaped as the cylindrical structure of rolled and plastered layers in metal cans with electrolytes. In the stacked form, the three layers are confined in laminate film and where their edges are heat-sealed aluminized plastic. A gel or polymer is often used to prevent the electrolyte from leaking in this package. For the energy source in EVs, Li-ion cells must be assembled into modules and then further composed into battery packs of series-parallel connected cells to achieve the precise energy demands [35].

III. TYPES OF LITHIUM-ION BATTERIES

In general, the main sources of the active lithium ions in a battery are the positive electrode material or the cathode. Hence, to achieve high capacity, a huge amounts of lithium is included in this material. Additionally, cathode materials follow a reversible process to exchange the lithium with slight structural modifications to its properties; in the electrolyte, the materials are prepared from reasonably-priced high lithium ions that have diffusivity, good conductivity and high efficiency [36]. Those types of cathode materials involve lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMn_2O_4$), lithium iron phosphate ($LiFePO_4$), lithium nickel–manganese-cobalt oxide ($LiNiMnCoO_2$), lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$) and lithium titanate ($Li_4Ti_5O_{12}$) [37].

A. LITHIUM COBALT OXIDE ($LiCoO_2$)

Lithium cobalt oxide was created by Sony in 1991, and Mizushima improved the material, as mentioned in the progression of patents [38], [39]. Its high specific energy makes this type of battery the usual choice for cells, tablets, laptops and cameras. However, there is the constrained accessibility of cobalt, which makes the cost high so that a replacement of the cathode materials would be required to increase its applications, for example, in EVs [40]. The battery is comprised of a cobalt oxide cathode and a graphite carbon anode in a layered structure that release lithium particles to travel between them during charging and discharging [41]. It has a short life and restricted load capacities and is not able to be charged and discharged at currents out of its range [42], [43]. It requires protection against overheating and excessive stress while charging quickly, and the charge and discharge rate need to be limited to a secure level of approximately 1C [44].

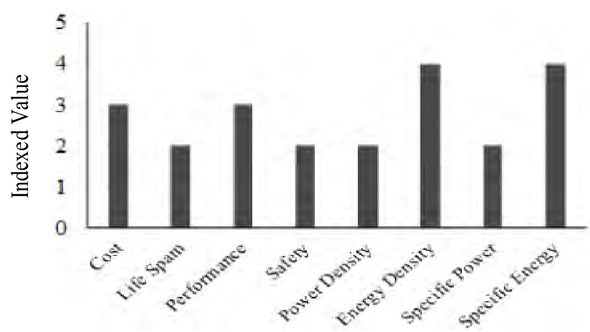

FIGURE 6. Li- cobalt battery performance.

Fig. 6 outlines the performance of Li-cobalt regarding specific energy or capacity, specific power or the ability to convey high current, energy and power density, safety, behaviour at different temperatures performance, life span, and cost. Li-cobalt with high energy density exhibits high specific energy yet moderate specific power, moderate safety, high price and long life span.

B. LITHIUM MANGANESE OXIDE ($LiMn_2O_4$)

Lithium manganese oxide was first introduced in the materials research bulletin in 1983 by Li *et al.* [45]. In 1994, the Bellcore lab built the lithium manganese oxide battery [46]–[48]. Its 3D spinel architecture was organized as a diamond shape which allows the particle to steam on the electrode so that it enhances current dealing and reduces internal resistance to charge quickly and discharges with a high current. Due to its spinel structure, it has positive impacts of high thermal stability and safety; however, it limits the life span. $LiMn_2O_4$ has more specific energy than cobalt [49].

The capacity of Li-manganese is approximately 33% lower compared with Li-cobalt. However, this type of battery provides approximately 50% more energy than nickel-based batteries. Design compliance permits specialists to enhance the longevity and high current handling of this battery. Think EVs have used EnerDel fabricated Li-ion battery pack and Nissan leaf EVs have used NEC manufactured Li-ion battery pack [50]. Lithium manganese oxide has a lower limit, 100 to 120 mAh/g, and a higher loss of capacity while charging or recharging cycle because of the extensive manganese disintegration in the electrolyte at raised temperatures [51]. In general performance, with the exception of power density, the current outlines of Li-manganese offer enhancement in specific power, energy density, well-being and life span, as demonstrated in Fig. 7.

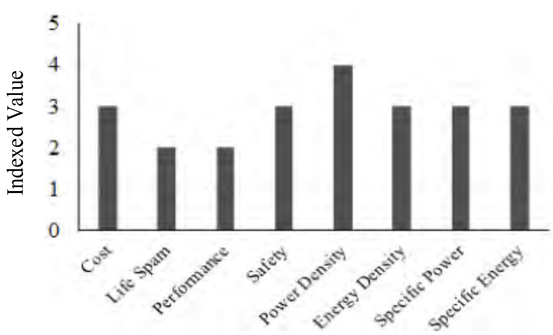

FIGURE 7. Li-manganese battery performance.

C. LITHIUM IRON PHOSPHATE ($LiFePO_4$)

The University of Texas found that phosphate could be used as a cathode material for lithium batteries in 1996. This cathode is steady in the overcharged condition and can tolerate high temperatures without breaking down; the cathode material in the lithium iron phosphate battery is more dependable and more secure than other cathode materials, e.g., $LiCoO_2$ or $LiMn_2O_4$ batteries. Phosphates exhibits cell operating temperature range of −30°C to +60°C and cell packing temperature range of −50°C to +60°C that deteriorates thermal runaway and prevents from burning out [52].

The lithium iron phosphate battery is made of nano-scale phosphate materials and exhibits a low resistance, long life span, high-load handling capability, improved security and

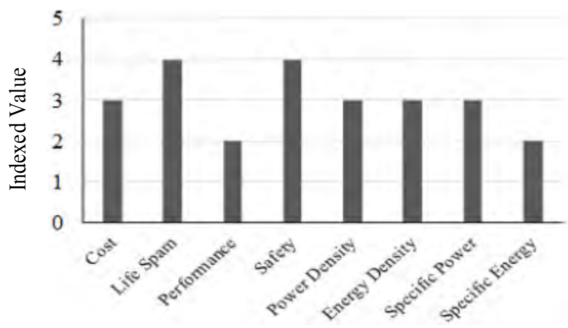

FIGURE 8. Li- phosphate battery performance.

thermic consistency, no toxic effects and less expense. It has less impact on the life cycle for overcharging and undercharging, although the specific energy is diminished marginally but is less than that found in $LiMn_2O_4$. It has some negative performance and service life properties due to temperature. Li-phosphate batteries are capable of providing a specific energy and nominal voltage of approximately 160 mAh/g and 3.40 V, respectively [53]. These attributes make the battery performance simple to upgrade [54]. Fig. 8 provides details of the characteristics of Li-phosphate.

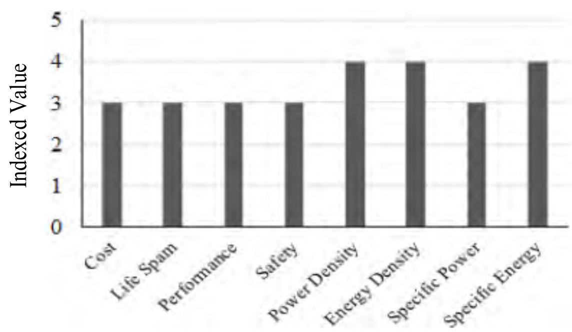

FIGURE 9. NMC battery performance.

D. LITHIUM NICKEL MANGANESE COBALT OXIDE ($LiNiMnCoO_2$)

Currently, battery companies concentrate on a cathode blend of nickel-manganese-cobalt (NMC). These cathode materials are oriented to establish either high specific energy or power with high density. For the silicon-based anode, the capacity and life cycle compromise each other. The combination of nickel and manganese exhibits good overall performance, drawing out the high specific energy of nickel and the low internal resistance effect of manganese, although nickel is low stable and manganese provides low specific energy [55]. The cathode mix of 33% nickel, 33% manganese and 34% cobalt offers a novel mix that brings lower raw material costs because of the decreased cobalt content. For the perfect mix, manufacturers protect their specific formulas. Presently, this battery is in great demand for EV applications due to their high specific energy and minimum self-heating rate. Fig. 9 shows the attributes of the NMC.

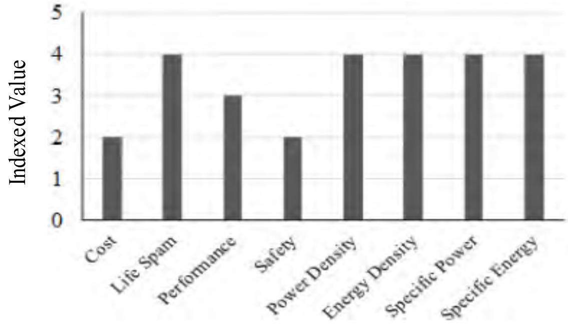

FIGURE 10. NCA battery performance.

E. LITHIUM NICKEL COBALT ALUMINIUM OXIDE ($LiNiCoAlO_2$)

The lithium nickel cobalt aluminium oxide battery (NCA) has a small amount of the world market share [56]. Now automobile industries are emphasizing NCA battery production because of its high profile i.e., high specific energy and power densities and long life span considering cost and safety [57]. Fig. 10 exhibits the properties of NCA and the areas for further advancement.

F. LITHIUM TITANATE ($Li_4Ti_5O_{12}$)

Lithium-titanate anodes have been commonly used for batteries since the 1980s [58]. It has a spinel architecture and is a substitution for the graphite anode of the Li-ion battery. It is normally 2.40 V and shows a high capacity, a high charge and discharge rate, and a high life span compared to that of a typical Li-ion battery [59]. Moreover, $Li_4Ti_5O_{12}$ batteries can be operated safely and have phenomenal features at cold temperatures. Because its specific energy is not high, unlike other Li-ions, the developments and research are focused on enhancing the specific energy and reducing the price [60]. Fig. 11 represents the attributes of the Li-titanate battery.

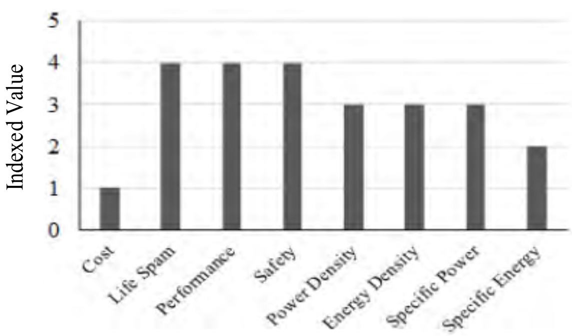

FIGURE 11. Li-titanate battery performance.

IV. LITHIUM-ION BATTERIES APPLICATIONS

From the discussion above, it is cleared that Li-ion batteries render high energy density and are lightweight. Therefore, Li-ion batteries are an important and suitable applicant for the next generation of aerospace, biomedical applications [61] and new automotive applications, especially new generation EVs and HEVs [62]–[66]. It is more efficient and effectual to arrange a number of battery cells in series or parallel as a battery pack for powering the heavy electrical and electronic devices, e.g., EVs, HEVs, air-vehicles, automated and remote controlled systems, and other power tools and machineries, than to connect a huge capacity battery [67].

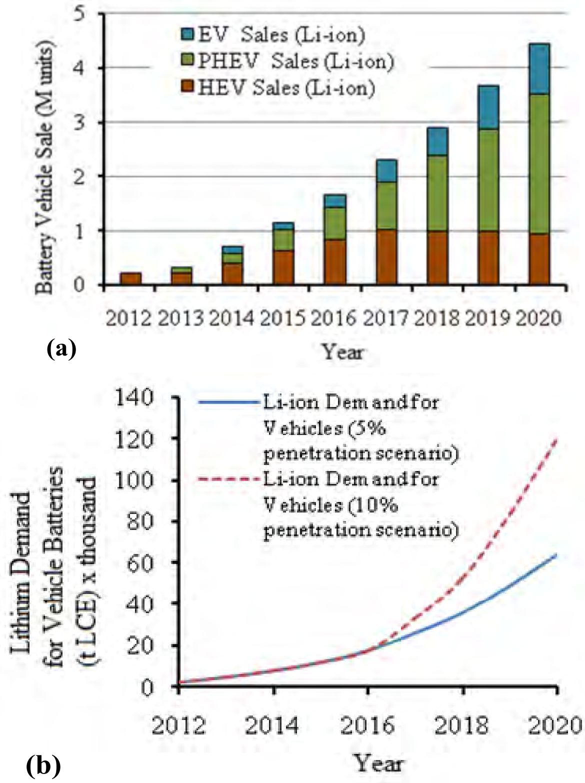

FIGURE 12. (a) Lithium-ion battery vehicle sales, (b) Lithium demand for vehicle batteries.

Fig. 12 depicts the real scenario with projections for Li-ion battery vehicle (EV, PHEV, HEV) production and lithium demand for electric vehicle batteries i.e., the Li-ion battery demand in the world from 2012 to 2020 [68]. Here, it is seen that electric vehicle sales have been increasing gradually and that the production growth will continue in the future due to the public's demand for alternatives to conventional vehicles. To power electric vehicles, the lithium supply for batteries also rises as EV sales increase.

In addition to its application in automobiles, lithium-ion batteries also occupy a large field as a source of power in the telecommunication sectors. With proper handling, these batteries can be used for a secure backup power source for electric and electronic loads in an entire telecommunication network arena. In most cases, secondary non-aqueous Li-ion batteries are applied in these sectors [69]. In some large size applications of Li-ion batteries, it is recommended that the regulatory requirements should be maintained to combat the explosion risk and to save the lives and environment by providing accurate instructions and information materials [70].

V. PERFORMANCE COMPARISON LITHIUM-ION BATTERY

As discussed in the previous sections, the Li-ion battery is the most feasible battery used to attain fair and effective transportation to sustainable global development. Soon, battery run vehicles, e.g., EVs, HEVs, PHEVS and BEVS, will reign the automobile and aerospace industries and markets. Therefore, the performance comparison for all batteries is discussed as follows.

TABLE 1. Comparison between lithium-Ion battery with other types of batteries.

Battery Type	Lead-acid [71]	Ni-Cd [72]	Ni-MH [73]	Zn-Br [76]	Fe-Cr [75]	Li-ion [78]
Energy Density(Wh/kg)	30-50	45-80	60-120	35-54	20-35	110-160
Power Density	180	150	250-1000	-	70-100	1800
Nominal Voltage	2V	1.25V	1.25V	1.67V	1.18V	3.6V
Operating Temperature	-20-60°C	-40-60°C	-20-60°C	-20-60°C	-40-60°C	-20-60°C
Cycle Live	200-300	1500	300-500	>2000	-	500-1000
Charge Efficiency %	79	-	-	-	-	100
Energy Efficiency %	70	60-90	75	80	66	80
Voltage Efficiency %	-	-	-	-	82	-
Overcharge Tolerance	High	Moderate	Low	High	Moderate	Very low
Self-discharge	Low	Moderate	High	Low	High	Very low
Thermal Stability	Least Stable	Least Stable	Least Stable	Least Stable	Stable	Most Stable

A. PERFORMANCE COMPARISON LITHIUM-ION BATTERY WITH OTHERS BATTERIES

There are different types of conventional batteries such as lead-acid batteries [71], nickel-cadmium (Ni-Cd) batteries [72] and nickel-metal hydride (Ni-MH) batteries [73], [74]. Table 1 shows the comparison between Li-ion battery with other types of batteries. Li-ion batteries are superior in terms of high energy efficiency and power density, which allows them to be designed lighter and smaller in size. Moreover, other advantages of Li-ion batteries include a broad temperature range of operation, rapid charge capability, relatively long cycle life, low self-discharge rate and charge, energy, and voltage efficiency [75], [76]. For these lucrative characteristics, Li-ion batteries dominate commercial battery markets for powering bio-implanted devices, medical instrumentations and portable devices. Fig. 13 depicts the typical discharge characteristics of commercially available rechargeable battery sources, namely, lithium ion (Li-ion), lead acid, nickel-zinc (Ni-Zn), nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and zinc-manganese oxide (Zn-MnO_2) [75], [77], [78]. Almost all these battery sources have smooth and flat discharge characteristics with their own

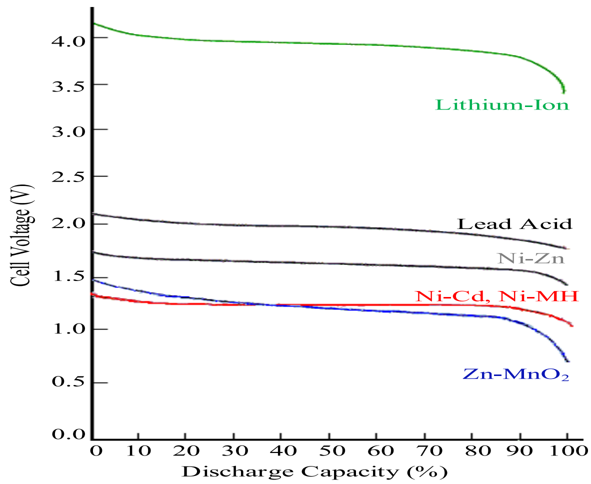

FIGURE 13. Typical discharge characteristics of Li-ion, lead acid, Ni-Zn, NiCd, NiMH and Zn-MnO$_2$ cells.

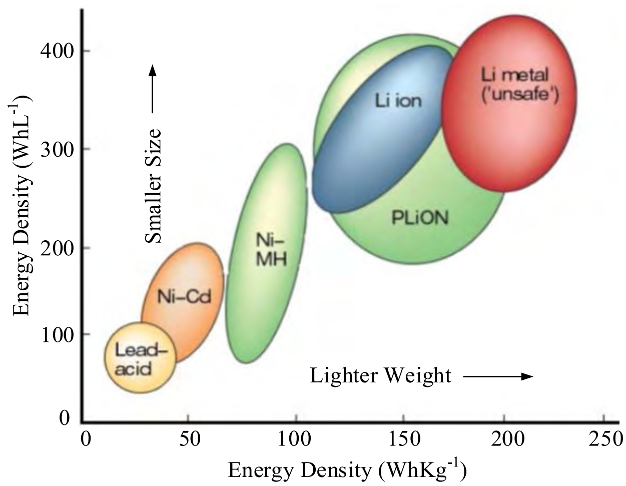

FIGURE 14. Gravimetric and volumetric energy density of various battery types.

specific energy and power levels; however, the Li-ion battery has slightly linear discharge characteristics. Moreover, in Fig. 14, the comprehensible differences among them are revealed in regard to their sizes and weights [38]. Here, it is shown that Li-ion batteries expose the best technology in high energy density with the smallest size and the lightest weight.

B. PERFORMANCE COMPARISON AMONG LITHIUM-ION BATTERIES TYPES

Although Li-ion batteries bear excellent characteristics, as explained in section 2, the basic differences among the Li-ion battery types are in the material that is used as an electrode in the battery. Here, the operating voltage characteristics of all lithium electrode materials are presented in Fig. 15 [41]. As positive electrodes, $LiCoO_2$ has good performance, however, it still has a high cost. Co is a limited resource and has low capacity. $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (LCA) and $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC) have high capacities and

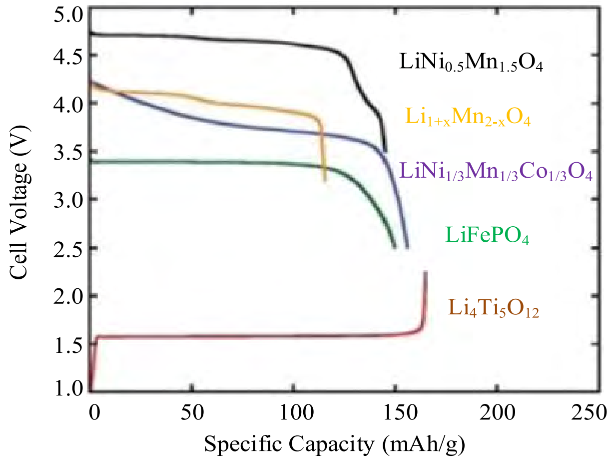

FIGURE 15. Operating voltage profile of all Lithium electrode materials.

voltages, outstanding performance, yet high prices. Ni and Co are limited resources; NMC is safer than LCA. $LiMn_2O_4$ variants have a low price due to availability of Mn, high voltage, average safety, and splendid performance but a limited cycle life and poor capacity. $LiFePO_4$ has good safety, cycling and performance, teeming of iron, and low price and toxicity but low voltage, capacity and energy. As negative electrodes, graphite has a long life cycle, copious yet comparatively low energy density, and inefficiencies due to solid electrolyte interface formation; $Li_4Ti_5O_{12}$ is a "zero strain" material that has good cycling and efficiencies although the voltage and capacity are low [78].

The performance comparison among Li-ion battery types, including advantages, disadvantages and applications are outlined in Table 2. Fig. 16 compares the specific energy, specific power, energy density, power density, cost, safety issues, overall performance and life cycles of the various lithium battery types. Superficially, it can be concluded that lithium-titanate is the best in terms of safety, performance, lifecycle and economy yet still poor in capacity and power categories. Lithium nickel manganese/cobalt has moderate properties, and others are average. To consider the application of Li-ion batteries in electric vehicles, the life cycle and safety features should be more significant than the capacity.

VI. LITHIUM-ION BATTERY MANAGEMENT SYSTEM

Li-ion battery powered EVs are becoming very effective and applicable as clean transportation alternatives throughout the world. The HEV and BEV systems can have a positive impact in the global economy and environment. To enhance its performance for service length, EV systems need to be safely maintained, including the safe operation of the ESS in the vehicle that is vital to EV technologies. The battery management system (BMS) manages all the control and management facilities regarding the energy storage and transfer in EV systems such as charging and discharging control,

TABLE 2. Performance comparison and applications among lithium-Ion battery types.

Types of Li-ion Batteries	Advantage	Disadvantage	Applications
$LiCoO_2$ [41]	High specific energy	Short life span and limited load capacity, and safety.	Cell phones; laptops and digital cameras
$LiMn_2O_4$ [49]	Specific power, safety and life span	Moderate in overall performance.	EVs, HEVs, medical.
$LiFePO_4$ [52]	Good thermal stability, tolerant to abuse, high current rating, excellent safety and long life span;	Moderate specific energy; lower voltage than other lithium-based batteries; cold temperature reduces performance	EVs; power tools and portable devices.
$LiNiMnCoO_2$ [55]	Good overall performance and excels on specific energy	High Cost	Power tools, electric vehicles and energy storages.
$LiNiCoAlO_2$ [57]	High energy and power densities, good life span	High cost and marginal safety	Electric vehicles and power trains.
$Li_4Ti_5O_{12}$ [60]	Temperature range (-30-55°C) and recharge efficiency 98%, life cycles: > 3000-7000 cycles, high safety and stability, quicker to charge, charged at rate > 10^{0}C.	Small voltage (2.4V/cell), low energy density, difficult to manufacture	Advanced nano-technology applications.

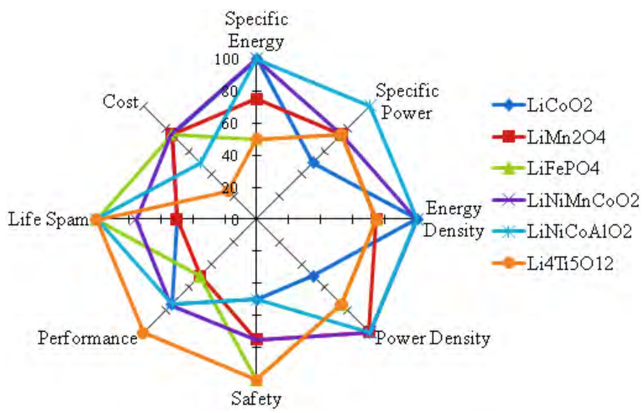

FIGURE 16. Comparison among lithium-ion battery types indexed values.

battery cell voltage monitoring and balancing, battery charge equalization, input/output current and voltage monitoring, temperature control, battery protection, fault diagnosis and assessment and so on [79]–[82]. The overview of BMS functions is presented in Fig. 17 [79]–[82]. The BMS controls the charging of battery as per the battery properties and the charge state of the battery. It controls the battery discharging on the basis of the load demand and the charge available in the battery systems. The battery cell voltage levels need to be measured by the BMS to estimate the charge states of the battery cells and to protect the cells from overcharging and undercharging. The battery cell balancing through charge equalization techniques should be implemented by the BMS to enhance the overall performance and life of batteries. The BMS controls the operating temperature at certain levels to

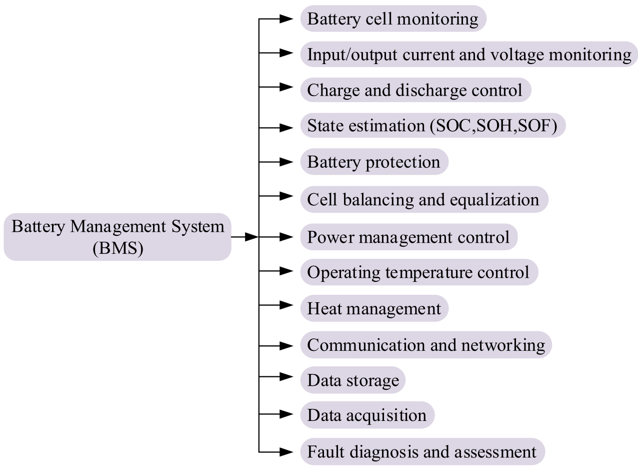

FIGURE 17. Overview of battery management system.

perform the energy conversions and manages the heat for safe operation. The protections from voltage/current stress, overvoltage, short-circuit, overcurrent, hysteresis, etc., are affirmed by incorporating sensors, relays, and breakers in the BMS of EV systems. The BMS diagnoses and assesses the faults that usually take place in EV systems concerning the entire processes of energy storage and power delivery. The details are described as follows.

A. BATTERY CELL MONITORING

The EVs use a series Li-ion battery cells in a pack. The battery cell may behave differently during the run-time. Therefore, continuous battery cell monitoring is needed for investigating the cells' conditions. The battery cell monitoring results might aid the system performances by managing, protecting, equalizing and controlling operations. It indicates the necessity of the charge and discharge control, the protections from the overcharged and undercharged cell conditions, the control of the temperature and heat, the communication and interface for data acquisition, and the fault diagnosis and assessment, etc. [79], [83].

B. INPUT/OUTPUT CURRENT AND VOLTAGE MONITORING

The Li-ion battery cells require constant current charging to maintain a constant voltage during operation. The abnormal change in the battery current and voltage values may cause system failure or system burnout. Thus, the monitoring of the current and voltage levels of battery cells is essential for protecting the cells from the over-current/voltage and under-current/voltage operations [83]. In addition, the records of the current and voltage values present the status of the energy storage system so that the EV can make the decision for further action.

C. CHARGE AND DISCHARGE CONTROL

The performance and durability of the Li-ion battery depends mainly on its charging and discharging. The optimized and quality charging and discharging of the Li-ion battery enhance the efficiency and life-cycle of the battery storage system. The efficient charging and discharging controls remove the memory effect and boost the discharging period of the battery. It is recommended to charge the Li-ion battery by the CC-CV (constant current- constant voltage) charge optimized PI (proportional-integral) controller and to discharge the Li-ion battery by the DCM (discontinuous current mode) discharge control [83].

D. ESTIMATION

The battery states include the state of charge (SOC), the state of health (SOH) and the state of function (SOF). The SOC defines the charge status and the discharge depth of the Li-ion battery. The SOC is estimated by means of an algorithm such as the discharge test method, coulomb count method, open circuit voltage method, sliding mode observer method, battery model-based method, neural network model method, fuzzy logic method, impedance method, internal resistance method, Kalman filter (conventional, extended, unscented, adaptive cubature etc.) method, H-infinity filter and so on, depending on the current, voltage and temperature values of the battery cell [84]–[90]. The SOH defines the present status with respect to the ideal status of the battery, which depends on the internal impedance, capacity, power density and the self-discharge rate of the battery. The SOH indicates how much the battery has been abused and if its performance has been degraded [87], [90]. The SOH is estimated by the durability model-based open-loop method that is executed by observing the mechanism of lithium ion loss, the side reactions, the capacity fade and incremental of internal resistance and the battery model-based parameters identification closed-loop method that is implemented by estimating the battery model parameters [90]. The SOF defines the real scenario of the battery performance in accomplishing the demand of the EV systems as the ratio of the remaining energy to the maximum energy of the battery. The SOF can be determined with the estimated values of the SOC and SOH, the charge/discharge profile and the operating temperature [79]. The battery state values might visualize and predict the overall condition and the performance of the Li-ion battery storage system in EVs so that the necessary actions might be taken accordingly.

E. BATTERY PROTECTION

Li-ion batteries are applied for energy storage systems in EVs with a number of series-connected battery cells in a pack. EV batteries may be charged from the external source and discharged to run the EV driving motor and systems [91], [92]. The consecutive charge-discharge cycle may cause a voltage and charge imbalance among the battery cells because of changes in their physical characteristics. This imbalance happens due to manufacturing, temperature, and cell ageing problems. Imbalanced voltage and charge profiles may reduce the overall performance and durability of energy storage systems [90]. Fig. 18 shows the charge imbalance among battery cells.

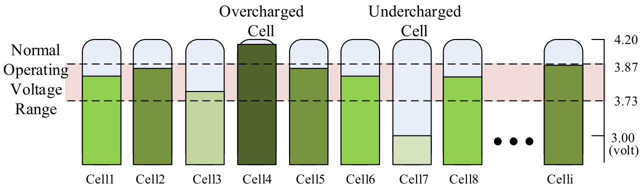

FIGURE 18. Charge imbalance among battery cells.

FIGURE 19. Safety problems of lithium-ion batteries.

Overcharging might cause cell explosion, whereas undercharging might damage the chemical properties of the battery and shorten the life of the battery cells [93], [94]. The battery imbalance scenario is shown in Fig. 19. The BMS may terminate the charging and discharging of the battery when it is out of the operation range. Thus, the battery pack may lose the rated charge level needed for the operation. Therefore, the charge equalization controller for the series connected battery pack is essential to protect the battery cells and to maintain the storage capacity and operation rating.

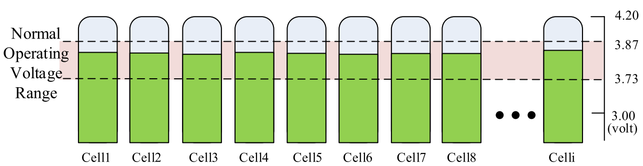

FIGURE 20. Protection, monitoring and charge equalization.

F. CELL BALANCING AND EQUALIZATION

BMS with individual cell monitoring and charge equalization could save battery cells from anomalies caused by overcharging and undercharging and enhance the overall performance of an energy storage system to power EVs effectively [83], [94], [95]. The CEC continuously monitors the voltage, current and temperature of the battery cells and detects an imbalanced cell through estimating the state of charge (SOC) of the battery cells. The equalization process is performed by transferring the excess charge from the overcharged cell to another cell/module/pack or by transferring the required charge to the undercharged cell from other adjacent cell/module/pack so that the cells become at an equalized charge or voltage level within the operating range. Fig. 20 shows the charge equalization for N-cells of a Li-ion battery pack. The equalization control might protect the batteries from damage and enhance the efficiency and lifecycle of the battery pack. However, the EV utilizes 90 or more battery cells in a series pack, and the individual monitoring and equalization management is difficult due to the design and control complexities, size and cost. Hence, the development of the BMS is necessary to employ the efficient cell monitoring and charge equalization with a simple design and control.

G. POWER MANAGEMENT CONTROL

Minimization of power abuses and losses is the present research challenge for the well-balanced and effective distribution and utilization of power in EVs. Without managing the power to drive the system and other loads, the overall system performance is reduced [96]. Moreover, electric and electronic machineries, tools and devices become less efficient due to unusual operation and unstable power supply. Power management system and control is the solution for managing the stabilized power distribution and controlling the EV load system efficiently and intelligently. To consider all factors and challenges on SOC, SOH and ageing for controlling and managing the power feed to the EV load system, the optimal power management and control is vital for enhancing the system performance, durability, security, and power quality and to reduce losses and operation and maintenance costs [97]. Currently, automated system control and management with optimal power management is being implemented in EV systems.

H. OPERATING TEMPERATURE CONTROL

The Li-ion battery storage system in an EV needs to be operated at a certain temperature. The temperature control system monitors the temperature condition of the battery storage system. It ensures that the Li-ion battery storage is operated within the operating temperature range. Otherwise the temperature control scheme provides feedback to the heat management and cooling system. The continuous monitoring and control of the temperature of the battery storage system in the EV maintains the efficient operation of the storage system and protects the battery pack from explosion [83].

I. HEAT MANAGEMENT

The Li-ion battery pack requires the equal distribution of temperature during the EV operation. Based on the temperature control operation of the BMS in the EV battery storage system, the heat management decides to operate the cooling or heating system, to regulate the power of the cooling or heating system and to provide the abnormal scenario of the battery storage system for extreme maintenance.

J. COMMUNICATION AND NETWORKING

The EV system requires communication with the vehicle subsystems and the inter-networking systems. It is necessary to optimize the performances in the EV and to accomplish the online monitoring, celebrating, programme downloading and updating and controlling the modifications for the BMS. Moreover, optimal EV charging station identification and drive range prediction are completed via the GPS (global positioning system) and the CAN (controller area network) by online SOC and SOH estimations of the battery storage system.

K. DATA STORAGE

The BMS requires the storage of data from the EV battery storage system, such as the voltage and SOC values of every Li-ion battery cell, temperature sensors' records, charge and discharge conditions, control program and so on. The BMS processes the stored data for equalization of the battery cells, heat management, fault diagnosis, and control of the other functional parts via the BMS controller. The BMS controller is connected with the main controller of the EV where the EV controller supervises the BMS actions and produces decisive outputs.

L. DATA ACQUISITION

The BMS extracts the present features of the Li-ion battery storage system by the data acquisition system. The data acquisition system consists of the sensors, measurement hardware, processor and software. It accumulates and stores data from the battery storage system such as voltage, current and temperature. The stored data in the BMS is processed by means of some functional and control algorithms.

M. FAULT DIAGNOSIS AND ASSESSMENT

The Li-ion battery storage system experiences some problems such as imbalance, undercharge, overcharge, overcurrent, and excessively low or high temperatures. In addition, the BMS experiences data acquisition faults, electric connection errors, communication and networking faults, programing errors, isolation problems and so on. The BMS is required to assess and diagnosis the faults and to take the necessary actions accordingly using diagnosis technology. The fault diagnosis technology is comprised of a system database and records, intelligent control program, communication networks and other technical measures [79]. The fault diagnosis and assessment of the Li-ion battery is conducted on the basis of an analytical model, knowledge and signal processing methods [79]. The research conducted on the fault diagnosis are advancing rapidly to facilitate Li-ion battery safety and development in EV storage applications.

Presently, the BMS has become an important issue for maintaining and managing battery storage systems in EVs. As a whole, the BMS functions to execute all purposes according to the acquired data from the battery and input/output systems, and sensors so that it can communicate to the storage, load, user-interface and display-alarm systems by perfect management. Therefore, as the technologies in advanced Li-ion battery development are growing, the improvement of the performance of the BMS in EV applications is important to prolong the lives of the batteries and to ensure its reliability and efficiency along with the accurate appraisal of the Li-ion battery status to the energy management system.

VII. ISSUES AND CHALLENGES

Li-ion batteries have many positive aspects: high potential and density (Wt/kg), minimum size, no memory effect, quick charge and high load handling, wider operating temperature range, no air condition required, high life cycle, and a longer service and replacement timeframe. However, there are still a few problems facing this battery. In order to be a substitute for other batteries, the problems should be specified and the respective suitable solutions need to be found. These problems include the protection circuitry, custom and cost, excitability of Li-ion safety, memory effect for partially numerous successive charge-discharge cycles, environmental impact and recycling [38]. The current challenges facing each type are outlined in section 2, the performance picture for each type of lithium battery, and in Table 2, the performance comparison and applications among Li-ion batteries. The summaries of the important challenges are as follows.

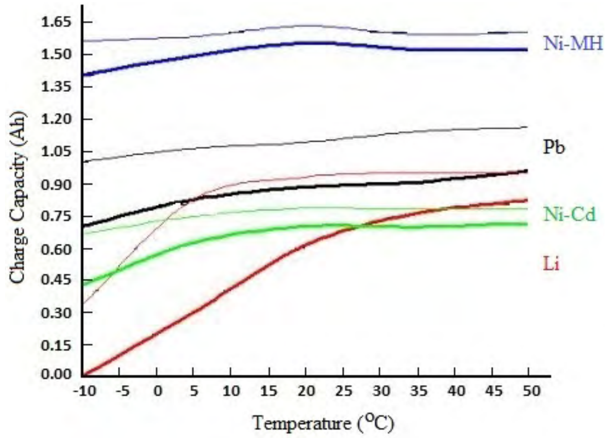

FIGURE 21. Lithium-ion and other common batteries' capacity variations with temperature.

A. TEMPERATURE

Temperature generation due to chemical reaction is a common problem for all batteries. Unusual temperature damages the chemical properties and kills the battery. More importantly, the temperature control mechanism is compulsory for the secondary lithium battery. Generally, the battery has to be operated at both low and high temperatures. For the low temperature effect, the charging and discharging current as well as power handling capacities of the battery are reduced due to the decreased rate of chemical reactions and the transformation of active chemicals with respect to temperature [51]. On the other hand, a higher temperature in the battery produces some difficult situations that cause the abnormal behaviour of chemicals and lead to the explosion of battery. Although some power can be reduced by stimulating the reactions by means of the Arrhenius effect, more current generates a higher temperature and results in thermal runway due to the positive feedback of temperature. Necessary steps must be taken to prevent the thermal runaway process in the battery. Fig. 21 represents the change of charge capacity of some rechargeable batteries with temperature during current feed and release [98]. The capacity of the Li-ion battery with other common batteries grows with the increase in temperature by sacrificing the life of the battery. This will be explained in the next section, "Life cycle".

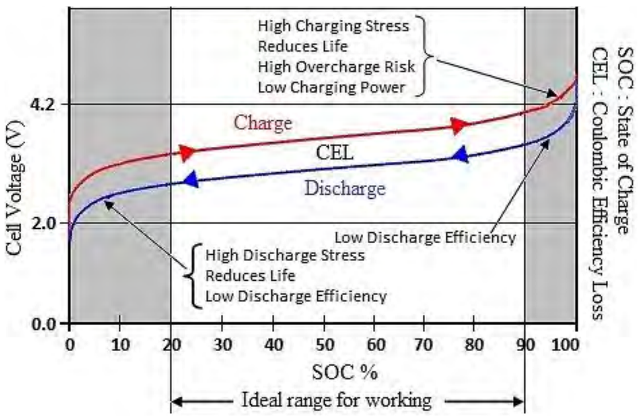

FIGURE 22. Evaluation of SOC for Battery cell protection.

B. SAFETY

The safe operation of Li-ion batteries is a great concern for scientists and engineers. The Li-ion battery pack is typically utilized with high power demand and some safety measures; moreover, a single Li-ion cell is never utilized for its explosive characteristics, unlike the NiCd battery. During its operation, the Li-ion battery requires additional elements and circuits to supervise the battery condition and operation and to protect the fault. For this reason, the development of Li-ion battery packs is more difficult than building and arranging batteries. Fig. 22 demonstrates the risk factors during overcharged and undercharged conditions of a cell beyond the SOC standard level. The safe operation, i.e., charging and discharging, of a rechargeable battery cell within the ideal working range of the state of charge (SOC), i.e., 20%-90%, can be accomplished by using a battery management system (BMS) [67], [99], [100].

C. LIFE CYCLE

The loss of cell function due to voltage and heat effects has been discussed; however, this loss has a negative effect on the cycle life of the battery. It is worth mentioning that if a battery cell operates out of its standard operating range, an irrevocable capacity loss occurs. This aberration causes a cumulative effect and lessens the life of battery, even possibly causing a total and permanent loss of use [101]. The actual life depends on the cell chemistry and the percentage of time spent at the upper and lower temperature limits, which are depicted in Fig. 23 [100]. The lifecycle falls slowly at a low temperature (below 10°C) due to anode plating, however, it decreases sharply at a high temperature (above 60°C) due to the chemical breakdown. Therefore, the ideal working temperature range should neither be too wide nor be too narrow due to lowering lifecycle and wasteful thermal management, respectively.

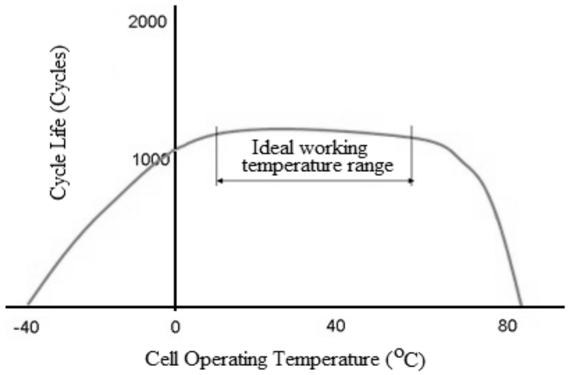

FIGURE 23. Lifecycle and temperature.

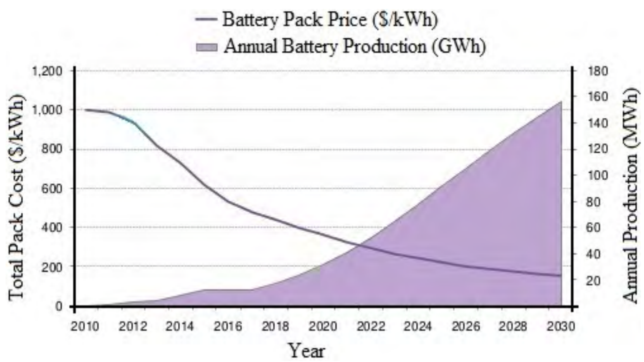

FIGURE 24. Cost and Production of lithium-ion battery pack.

D. MEMORY EFFECT

Memory effect is an effect to hold less memory in the battery. The effect arises due to repeatedly recharged after being partially discharged in irregular manner or many charge-discharge cycles at normal operation [102]. In EVs, the thing happens when the battery is recharged partially during the braking operation by the engine running in generator mode and then discharged partly to accelerate the engine. This partially numerous successive charge-discharge cycles lead to have memory effect in the EV batteries. It can be observed by the voltage profile of Li-ion battery at which the battery seems to be draining very hastily as voltage depression or deviation because of not holding its full charge [103]. This phenomenon might produce cell voltage imbalance in the series connected battery cell pack. The memory effect might be overcome by subjecting individual cell to deep charge-discharge cycle process by using optimal charge and discharge control technique [104].

E. COST

The price of lithium was extremely high a decade ago. However, its price has become more negotiable due to greater application, demand and production at the present time. The price of a Li-ion battery pack is 25%-30% of the price of an electric car [105], [106]. The market prices for Li-ion batteries have been decreasing over last five years, as illustrated in Fig. 24, so that the price has dropped almost 15%

in each of the past three years [106], [107]. It may fall by more than 25% by 2020, which was suggested in a study by *McKinsey & Company* [106]. *Boomberg New Energy Finance* predicted, as depicted in Fig. 24, that the price of the Li-ion battery pack will reduce to one-fourth of today's price by 2030 and that its production will grow with the decrease in its production cost [108]. The availability of lithium and its cost will depend mainly on the market demand for consumer utilities, advancements in EVs technologies and its use, growth of recycling, geopolitical issues, budge allocation and environmental impact, etc.

F. ENVIRONMENTAL IMPACT

Increasing the oil prices and the demand of enormous energy for sustainable transportation have caused a trend towards automobile electrification such as EVs, HEVs, and PHEVs. An estimation by *Toyota* claims that more than 7% of the world transportation will be by electric vehicle by 2020 [109], [110]. Although it has a great impact on the ecological environment by reducing the number of oil based vehicles, the Li-ion battery emits CO_2 and GHGs during production and disposal [111]. The US EPA examined Li-ion batteries for its use of nickel- and cobalt-based cathodes and solvent-based electrode processing in a study and found high environmental impacts, such as resource reduction, global warming, ecological toxicity and human health impacts and so on [112]. According to this study, the people involved in the production, processing, and use of cobalt and nickel metal compounds may be affected with adverse respiratory, pulmonary and neurological diseases [112]. This risk can be removed by adopting a Li-ion battery recycling process to save virgin resource materials and reduce the use of nickel and cobalt materials [112], [113].

G. RECYCLING

Currently, the Li-ion battery has greater demand to power future transportation and other applications. It has a negative impact on the environment, as discussed in the previous subsection. Recycling is a vital way by which environmental pollution can be decreased by reducing CO_2 and GHGs emissions [111]. The recycling process enriches the reservation of lithium, nickel and other materials by recovery [114] so that it improves the life cycle of batteries and shores up battery production [115], [116]. There are three basic recycling techniques: hydrometallurgical recovery, pyrometallurgical recovery, and direct recycling. Direct recycling allows for a higher percentage of the battery materials to be recovered, and the pyrometallurgical recovery process works at a high temperature [112]. Refurbishing batteries at the end of their life cycle or revitalizing them with new electrolytes will be possible in the future [117].

VIII. CONCLUSION AND RECOMMENDATIONS

Li-ion batteries are now becoming popular for powering EVs, electric and electronic portable devices, tools and utilities as alternative energy resources. Due to its high energy density, the devices that are powered by Li-ion batteries do not need to be recharged frequently. The lightweight properties make these batteries an easily accepted choice for use in portable devices. The market prices of Li-ion batteries have decreased continually since their introduction. Further price reductions are anticipated, which is anticipated to be approximately 75% of the present price by 2030. However, the price is still costly. In this study, a deep review of Li-ion batteries and other types of batteries was presented. A performance comparison is also presented. The safety concerns and negative environmental impacts of Li-ion battery were considered in this review with some criticism. An overview of the battery monitoring and management system, charge and discharge control, protection, state estimation, energy storage and assessment are explained towards improving the performance of the existing Li-ion batteries in EV applications. Issues and challenges regarding the safety, environmental impacts, performance and applications are highlighted for future research and development guidelines. Some significant and selective suggestions for further technological development and production of Li-ion batteries have been highlighted through this review as follows;

- The optimal use of the lithium electrode material according to its appropriate demand and application is essential;
- The development of battery management and charge equalization technologies with minimum cost of maintenance and operation due to safety issues and enhancing the life cycle need to be considered;
- The memory effect could be minimized by subjecting individual cell to deep charge-discharge cycle process by using optimal charge and discharge control technique;
- The environmental and health issues, which require sophisticated and controlled techniques during battery production and disposal;
- The availability of the processing machineries for battery recycling for reserving raw materials is important in most countries and;
- The augmentation of second-hand battery utilization by refurbishing is growing.

These suggestions offer a remarkable contribution towards the maturity of Li-ion battery technology. Thus, it is concluded that the further development of Li-ion batteries will dominate the clean vehicle market in the future.

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