



## Review Article

# Recent advances in lithium–ion battery utilization: A mini review

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## ABSTRACT

Lithium-ion (Li-ion) batteries have become popular recently by performing better than conventional batteries. With the advancements in battery technologies, the amount of energy stored by li-ion batteries increases, and important developments occur in control systems. In this article, temperature approaches to the design of advanced electrolyte solutions for Li-ion batteries, electrochemical and electrode effects are examined. As a result of the study, it was observed that the amount of energy stored by Li-ion batteries increased with the developments in battery technologies and that there were significant developments in control systems.

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## INTRODUCTION

As it is obvious today energy and energy storage play more important role than any time in our history. Figure 2 shows the global market values of the lithium-ion battery annually with the statistics from 1992 to 2020. To achieve the support of expansion in energy and power density, it is indispensable to imagine our future challenges for energy furthermore; energy storage by the use of new materials of chemistry. The general scheme of the battery has shown in the Figure 1. We should find paths for synthesizing new Nano-materials with up-to-date and latest properties, that can be used as electrodes or electrolytes in LIB's [1].

With the advancement of technology, interest in lithium-ion batteries is increasing. As the various articles revealed, the total consumption amount of energy increased drastically in a couple of years[6]. Also, energy usage in the countries with higher GDP is more than in other countries

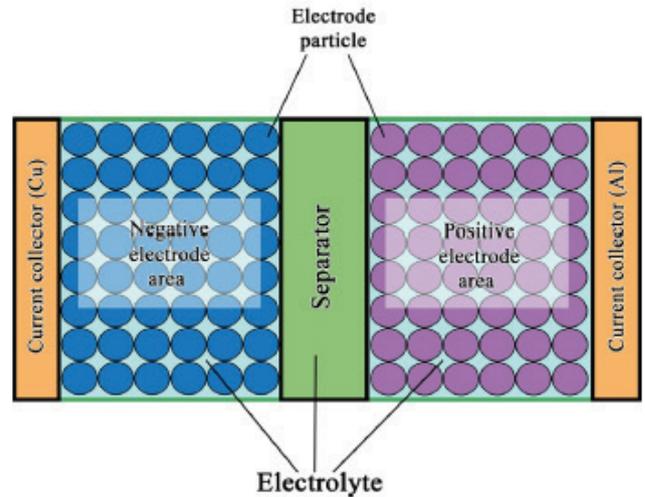


Figure 1. Illustrative sketch of LIB [2].

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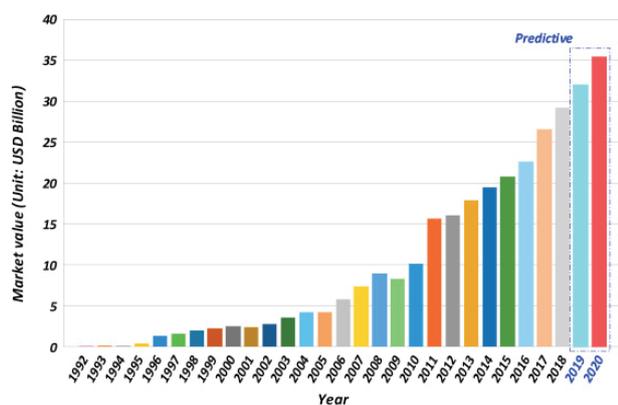


Figure 2. World market of LIB's from 1992 to 2020 [3–5].

[7]. Besides, results confirm the presence of a positive relationship between energy consumption and GDP per capita in both developed and underdeveloped countries [8]. The neutrality hypothesis reveals there is no causality between the consumption of energy and economic growth. The feedback hypothesis claims the presence of mutual interdependence of economic growth and energy consumption [9]. As word oil forecast from 2008 to 2030 demonstrates, fossil fuels production will be decrease promptly, which means countries will not have the chance to use that kind of fuel forever [10]. With regards to robust empirical findings, we can conclude that due to massive consumption of fossil fuels, the rapid degradation of the region's environment moreover, carbon emission has happened all around the world. Indeed, a majority of environmental challenges in so many regions are exacerbated by the consumption of fossil fuels. It means that burning fossil fuels and carbon emission has parallel and direct relation [11]. To surpass and diminish all the problems of fossil fuels and environmental problems one approach can be utilizing the renewable sources and energies like solar power, biofuel, etc. But the main problem in all these types of sources is their non-uniform energy output [12]. The most emphasize point due to the mentioned problems is to make a balance between the energy output and energy storage. The spirit item in the modern chain of energy supply is energy storage as the main factor to boost the grid stability and grow the penetration of renewable energy resources, affect the energy productivity of the systems above all, deplete the environmental impact of energy generation [13]. Though, to balance among the energy output and also the energy storage by employing the battery to reservoir energy. The battery utilizes a chemical reaction to convert the stored chemical energy into electrical energy and produce a voltage between two terminals. Batteries are used frequently in so different and various industrial and domestic fields. There are several types of batteries also Lithium batteries with diverse battery technologies are used in off-grid, on-grid, hybrid and energy storages of the vehicles fields [14]. Lithium

batteries component is lithium metal as an anode. The privilege of these batteries such as, safety, abundance and low cost of cathode material make them favorable for the future too. Lithium oxides and salts can be recycled which is the promising point of these batteries [15]. Li-ion batteries can be designed for different ranges of power and energy due to cell sizes, thicknesses of the electrode, also relative quantities of material can be used [16]. Lithium battery manufacturers can produce small portable also large industrial batteries as power sources by addressing a very large market from portable phones to EVs [17]. Lithium batteries has so many advantages despite that, factors such as safety concerns, thermal runaway, short-circuiting, toxic gas emissions, overcharging, high cost reflect pettifogging and performance issues in those batteries [18]. One of the most important factors in LIB's is safety. However, if they operated improperly, the chemical energy can be briskly rescued in the form of fire or explosions [19,20]. The other main concerns are the generated heat within the cell, which may be due the onset of thermal runaway [21–23]. Methods to ensure battery safety involve external or internal protection mechanisms External protection depends on external electronic devices like temperature sensors and pressure valves that increase the dead weight/volume of the battery. Internal protection relies on to focusing the inherent materials as battery elements and is considered being the summit solution for battery safety [24]. In recent times, the aging and deterioration of LIB cells and their reaction due to thermal effects and analyzing the effect of temperature has been studied and investigated in so many researches [25–35]. As the life cycle of LIB, thermal management is one of the key factors. Besides optimum operating temperature of Lithium-ion battery pack is about 25–40 °C [36]. Reports illustrate that Li-ion cell performance, due to capacity fade, is sensitive to the operating temperature [30,37]. Likewise, cell action is commonly defined with a technique as Electrochemical Impedance Spectroscopy (EIS) [34,38]. As mentioned above temperature plays a vital role in LIB's, also the increased temperature around LIB's has resulted from the heat generation phenomena of Lithium-ion cells that happened while charging and discharge cycles [39]. However, this study differs from existing papers in that it comprehensively analyzes the effects on the efficiency of LIBs and their use in various fields.

### Effect of Temperature

As Figure 3 reveals Lithium-ion batteries do not the look like the other type of batteries. In the other kinds, the temperature is so effective factor in their efficiency, e.g. the efficiency of the batteries has fluctuated due to the weather temperature. Although in LIB's the efficiency does not change and rises up and down regards the outside factors.

Researches demonstrate that power and capacity can diminish significantly while cells operated or are stored at temperatures above 50 °C and high States Of Charge (SOCs) [30]. One of the studies reports that high temperatures

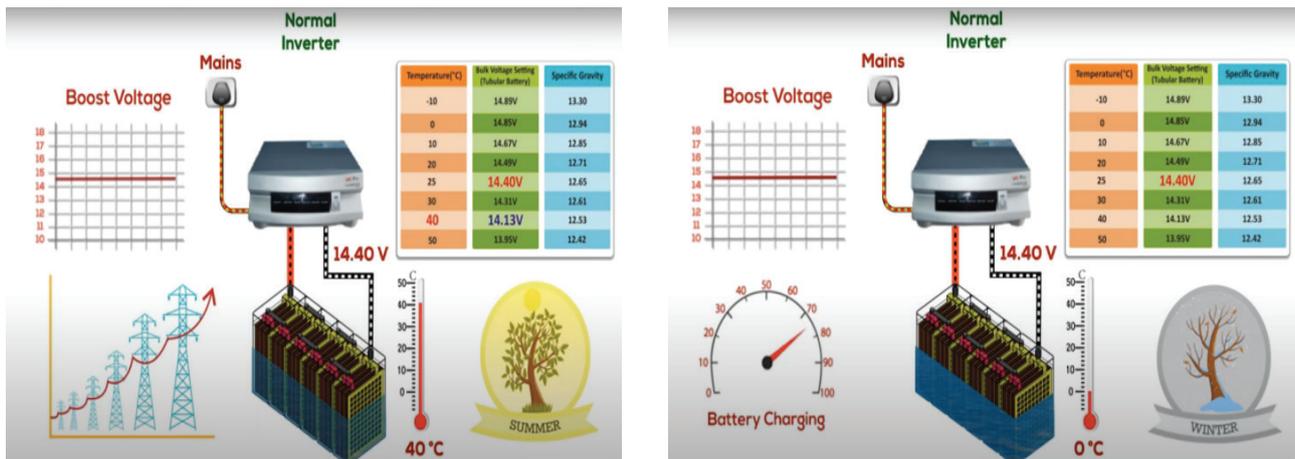


Figure 3. As the figure shows, LIB's efficiency remains constant as a result of seasonal changes [40].

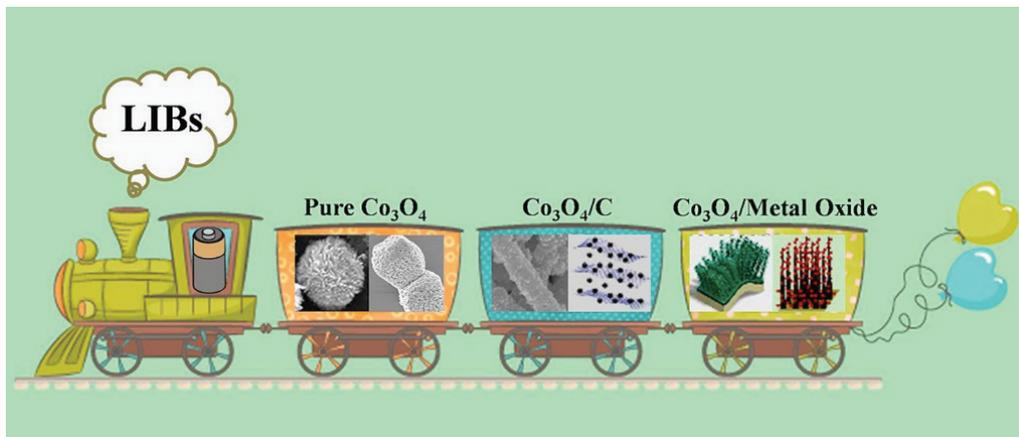


Figure 4. Lithium ion batteries anode materials [41].

hasten capacity decay, although temperatures, especially during charging, are also destructive, as they conduct the lithium plating and dendrite growth [25].

Figure 4. Shows various Cobalt oxides composites and inorganic materials are concerned on assorted industries. The major raw material as an anode for preparation of LIBs is  $Co_3O_4$ . Due to the researches which, illustrates  $Co_3O_4$  with obverse spinal constructions supposed to be used widely in new types of LIBs why has a great performance of high redox capacitance, physical effects and giant chemical freshness [41].

Figure 5, all the reversible and irreversible due to heat generation processes have been illustrated. Due to the figure, reversible process and entropy change on the electrochemical reactions. Moreover, it shows the irreversible process and active polarization process on charge transfer resistance, ohmic heating process on transport resistance in phases, heating due to mixing on inhomogeneous ion distribution, and finally enthalpy change on the diffusion of Lithium ions has been shown [42].

Figure 6 shows the different looming monitoring the internal temperature of LIBs regards the sealed nature reactions during operation. The approaches are classified in two brackets that include contact measurement and contactless measurement [42].

**Effect of temperature on Lithium ion batteries**

Figure 7 illustrates the effects of various temperature range and their effects on the negative electrode. Besides the effect of electrolyte decomposition has been depicted by details in the mentioned figure [43].

Figure 8 shows the results and consequences of high temperature on the cathode. Also, the depletion of viscosity by boosting the coating temperature enhances the productivity of the cathode [44].

Simply can be easily understood that thermal effect on Lithium ion batteries plays a vital role in the battery performance besides the battery safety. Though; to clarify the temperature effect on the batteries, one can note the thermal effects, which leads to the chemical reactions that happened in the batteries. Due to the chemical reactions, the

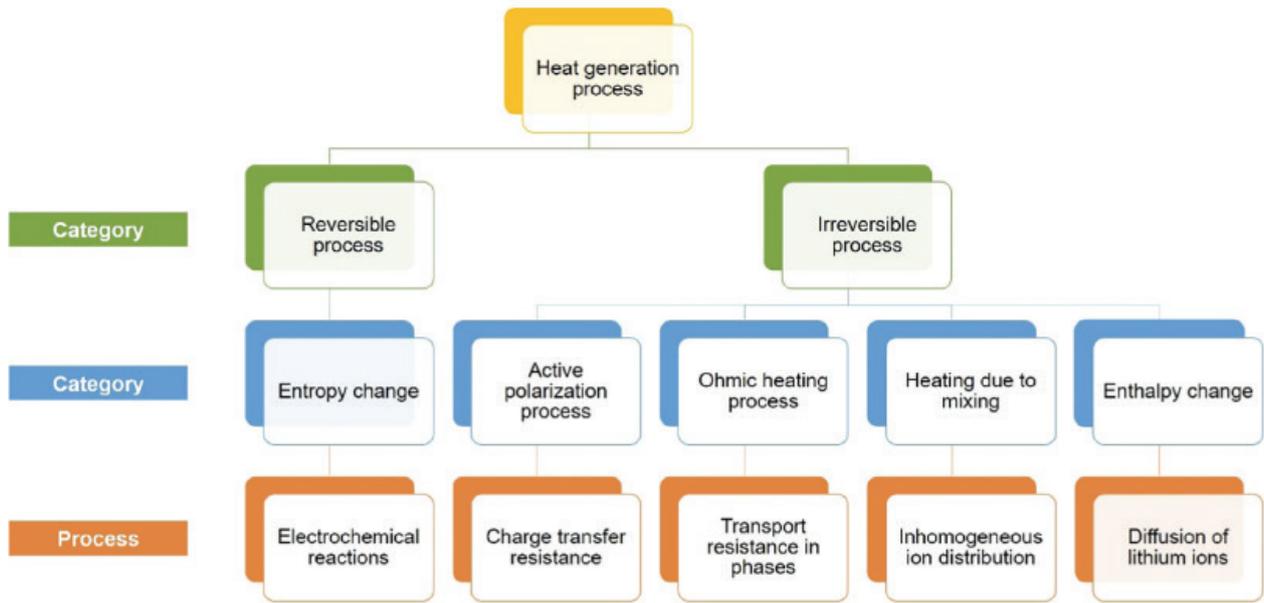


Figure 5. Heat generation reversible and irreversible processes in LIBs [42].

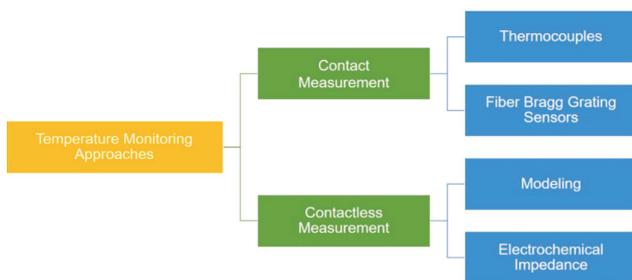


Figure 6. Systematization of temperature monitoring approaches [42].

connection among the changing rate of them and response of temperature that obey the Arrhenius equation [45]. In table 1 the thermal effects on the lithium ion batteries have been listed and depicted.

**Effect on electrolyte**

The electrolyte as part of polymer science is an interdisciplinary field that encircles the polymer and chemistry as electrochemistry, organic chemistry, inorganic chemistry [47]. Also, the science of polymer electrolytes was emerged [48]. The lithium-ion batteries that recruit a solid-state

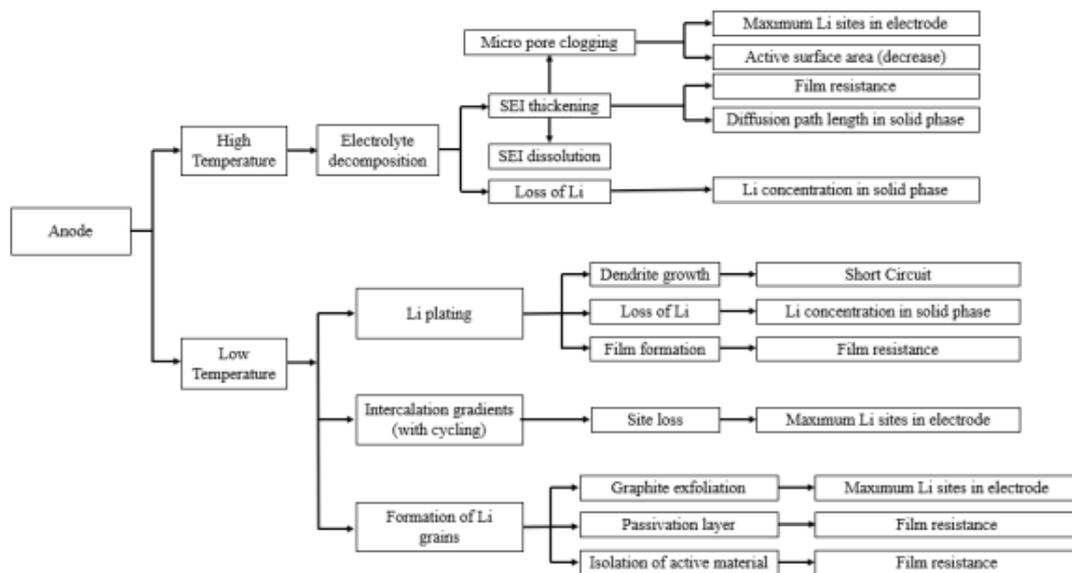
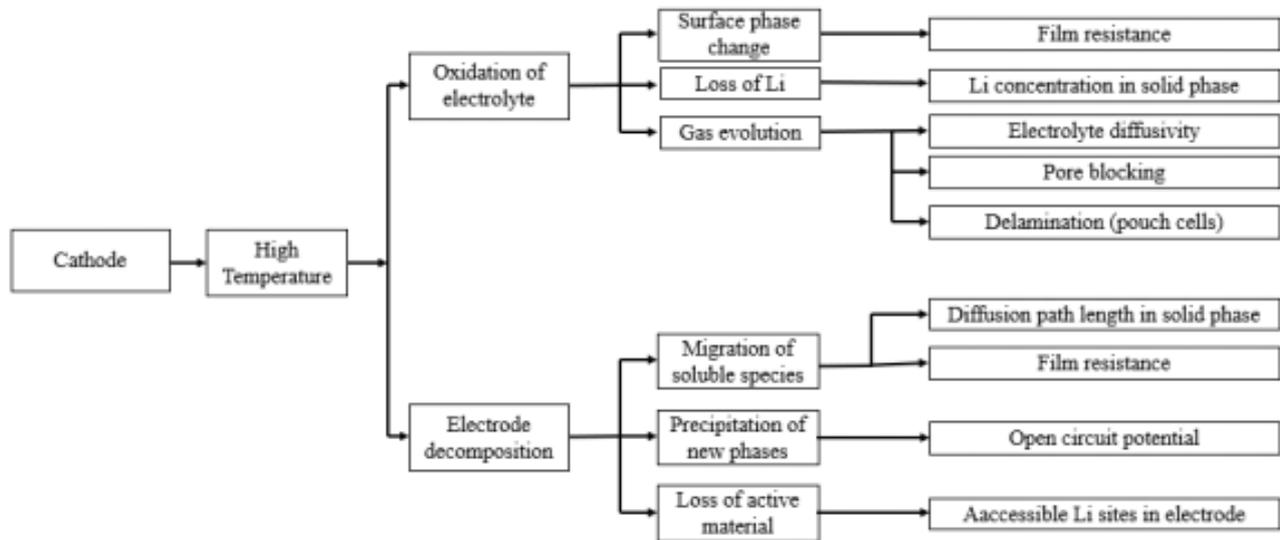


Figure 7. Negative electrode and temperature effect [43].



**Figure 8.** Positive electrode and temperature effect [43].

**Table 1.** The most effective factors as thermal effects on the LIBs.

Electrolyte decomposition [46].
Short circuit [46].
Electrolyte burning [46].
Separator melting [46].

electrolyte, due to the amount of flammability factor commonly are safer than the other types of electrolytes that utilize the liquid organic electrolytes. To improve the quality of all-solid-state lithium-ion batteries should have the qualifications such as giant conductivity of lithium ion batteries, good level of stability towards the chemical reaction with lithium in the anode part finally the good electrochemical capacity to use the high-voltage cathode materials [49]. As a general, there is the belief that states solid oxides electrolytes have more advantages regards to their chemical stability and handling in comparison with the inorganic materials. Otherwise, the lithium-ion conductivity of the solid oxide electrolytes is less than the liquid organic electrolytes and solid sulfide electrolytes [50–53].

### Thermal runaway

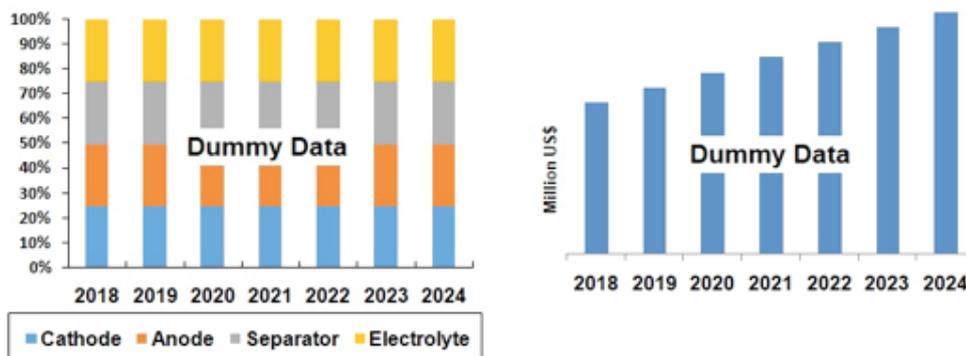
Nowadays by the rapid growth of population and as a sequence, huge needs for electric gadgets and equipment lithium-ion batteries and their role in the technology has been emphasized [19,54,55]. Nevertheless, safety in batteries still is the chief problem and concern for scientists. The major calamitous failure of the LIBs is their thermal runaway or simply TR, which should be avoided to be happened. Thermal runaway could happen as a result of overcharging, short circuits of the interior cell, or in some cases the collision of the gadget. Moreover, during the thermal

runaway chain reactions of sourcing the heat generation might be occurred [56–58]. Besides the exact source of the happening the thermal runaway mechanism of lithium-ion batteries need more comprehensive researches and investigations [59] as in some cases there is clear field failures thermal runaway also in others there are not clear causes [60].

### Cathode, Anode and Separator

As it is clear all kind of batteries involve the cathode, anode and electrolyte. The cathode is generally an oxide that embedded Lithium with very little chemical potential confirms a large open-cell voltage for the battery. Also Lithium intercalation causes remarkable electron move to the Oxygen ions in the structure [61]. Most research for cathode materials has concentrated on transition-metal oxides; the reason of this tendency is transition-metal oxide delivers a better cell voltage than most sulfides [61]. While the battery, which includes the Lithium-ion, has been charged  $\text{Li}^+$  ions are removed from the frame and moved through the electrolyte to the anode. Transfer electrons of the Li ions tends to de-stabilize the shape with regards to the increasing repulsion between the bare oxygen layers that face each other [61].

There are various effective items for designing and settling the materials and development. The most functional factors could be arranged by different scaling. The first one is energy density and it is the amount of energy that can be stored or kept in a special mass of a substance or system [62]. Also Density here determines the energy density with the articles reversible capacity or their operating voltage. In the second and third factors, electronic and ionic movability are the key factor [63]. The second factor is rate capability that relies on the fraction of maximum to minimum charge or discharge rate of a battery [64]. The



**Figure 9.** Global forecast for Lithium-ion battery market 2018-2024, Left graph shows the market share (percent) by materials, the right one reveals the market share by electrolyte [66].

third element is cycling life performance. It is the round of the full recharges numbers depending on time and charge or discharge cycles. Now day's batteries after reaching the maximum life cycle start to deteriorate faster and also their capacity to be recharged fully decreases [65]. The last two features are safety and cost. As it is clear the mentioned items should be assumed in the maximum level to reach the superior design [63].

### Cathode

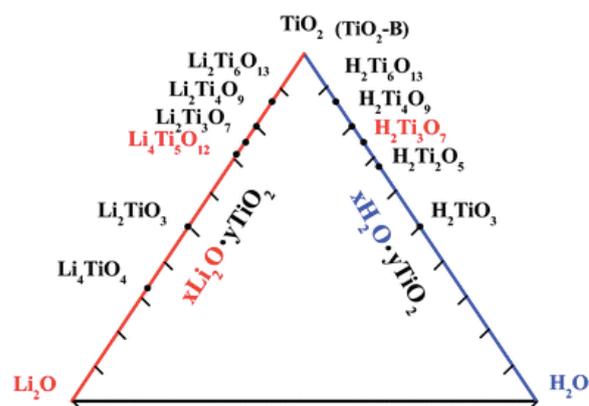
The three key components in batteries are cathode, anode and electrolyte. In today's trading LIB's, both anode and cathode materials are embedded materials. As we know from basic chemistry rules, the metal oxides in cathodes include of fixed host with specific sites for Lithium ions. Electrons tend to move from cathode to anode by the external current collectors, which are named as electric circuit. In Lithium-ion batteries the chemical potential of Lithium is higher in the anode due to the cathode, though electric energy is stored in the form of (electro) chemical energy [63]. The separators must separate the cathode and anode areas. The separator is a micro-porous membrane, which lets the electrolyte enter or prevent the shorting circuit of electrodes [63]. The cathode material is usually the most expensive one with highest weight in the battery, which justifies the intense research focus on this electrode. Even in figure 9, the battery market share of lithium-ion batteries shows the percentage of each cathode, anode, separator and electrolyte quantity from 2018 to 2024 years.

Lithium-ion Battery Market by Material has been divided into below groups [66]:

- LCO (Lithium Cobalt Oxide)
- NMC (Lithium Nickel Manganese Cobalt Oxide)
- NCA (Lithium Nickel Cobalt Aluminum Oxide)
- LMO (Lithium Manganese Oxide)
- LPF (Lithium Iron Phosphate)

### Anode

According to statistics for more than three decades Lithium batteries are used as energy storage technology also major power source in electronic appliance especially in different portable electronic devices [67,68]. The technology of the batteries is growing to be significant to the demands of large-scale devices that utilize the batteries. Though most important factors to meet their requirements like energy density and power performance are the research topics of the researchers. The market LIB's due to their energy amount and power density, as anode type arranged to graphite type and remain batteries, according to cathode type can be ordered in lithium-phosphate-based and lithium-metal-oxide type [69]. In Figure 10, potential alternative elements with reliable safety and steadiness cycling to traditional carbon-based anodes with tiny structure change have been revealed [70–72]. The development of high-capacity materials for LIB's principally for cathode and anode materials provide a great moment for the execution of modern and newest batteries [73]. In general for anode materials, three types of reaction mechanisms outlined



**Figure 10.** The phase diagram of Ti-based [78].

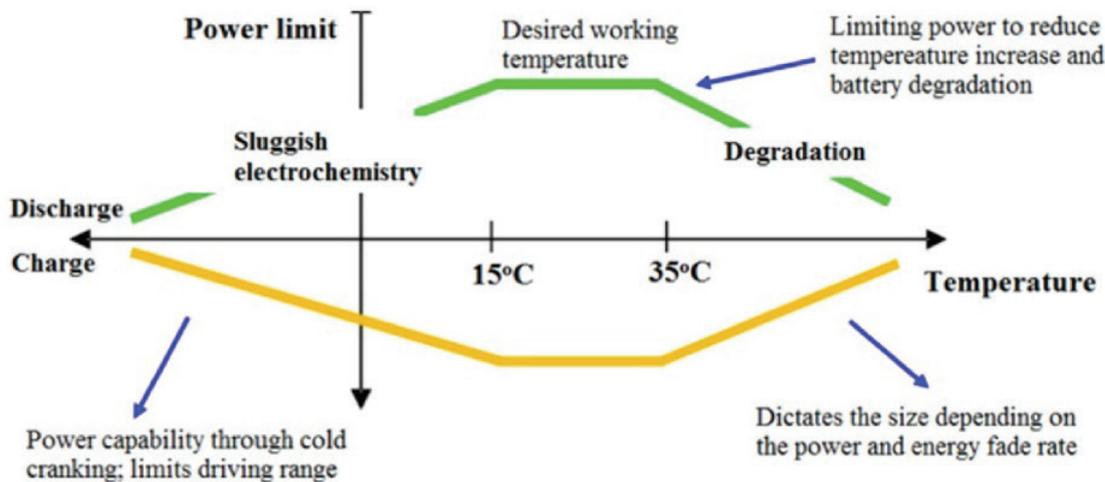


Figure 11. Working temperature interval of batteries [85].

[74]. A graphitic carbon is the mainstay as successful intercalation-type material for the anode in today's lithium-ion technology has commercialized [67,68]. Although the weaknesses of the graphite materials is their poor electrical conductivity of them even though their large irreversible capacity [75]. Over and above to classify the anode materials based on the intercalation reaction mechanism Ti-based oxides such  $TiO_2$  and  $Li_4Ti_5O_{12}$  [76–78]. Moreover, in the figure 10, the phase diagram of Titanium base batteries has been drawn.

### Solid-Electrolyte interphase (SEI)

Broadly the solid-electrolyte interphase or simply SEI is substantially for the existent operation of Lithium ion batteries, as principle and minor power sources [79]. Also, Peled in 1979 confirmed that the SEI model was reasonable for all alkali metals and; alkaline piles of earth in non-aqueous-battery systems [79]. Then the layer that formed directly, alongside contact of the metal with the solution, contains unsolvable and partly solvable cutting products of electrolyte components. The depth and diameter of the newly shaped layer are regulated and controlled by the electron-tunneling span. The layer functions as the interphase among the solution and the metal additionally, the layer has the possessions of a solid electrolyte with high electronic resistance [79]. Even the solid-electrolyte interphase is the key element that dictates the morphology, power capability and the most emphasized the safety of the lithium deposits and the cycle life of the batteries[80,81]. The SEI should be flexible and mechanically stable. Therefore, the cation transportation number must be close to unity. For this reason, the concentration polarization should be eliminated and the metallic anode dissolution/deposition process operated easily. Besides, to generate a protective SEI on the alkali-metal anodes, the vital point is the volume of the SEI materials should be larger than the amount of the anode, otherwise the SEI will not cover the surface and layer of the

anode completely, and results he corrosion on top of the anode [82]. The most emphasized factors for the SEI are such as: high electrical resistance of solid-electrolyte interphase or simply RSEI, the thickness close to a few nanometers, selectivity and permeability, giant amount of strength, toleration to the enlargement and growth of contraction stresses, amount of unsolvable character in the electrolyte, further the stability over a wide range of functioning temperatures and potentials [83].

### MATERIALS AND METHODS

Lithium-ion batteries or simply LIB are used increasingly as the principle of the electronic devices especially in vehicle markets and electronic vehicles (EV). Moreover, the performance of the mentioned batteries directly depends on the operating temperature and working voltage as shown in Figure 11 [84].

Bulk size of batteries in electronic vehicles face hard and harsh circumstances such as thermal, electrical and uncomplimentary loading that cause the short circuit and parallels deteriorated performance and explosion [30,86–99]. Reaction rates escalate while the temperature increases and leading the heat decadences and eliciting greater temperatures [100]. In this stage, if the produced heat will not evacuated drive the thermal runaway [101]. As consequences of the detritions in batteries thermal runaway (TR) could lead the deathly occasions. In reality, in modern battery, electrified vehicles, the most concern with vital priority is the safety of the system [102]. Though for battery safety it should be kept in a controllable environment where the temperature and heat gradient could be scanned and detected to prevented happening the thermal runaway and assure the safety [84]. As a result, there are various methods to cool down or prevent the causing the thermal runaway and manage the heat of battery Lithium-ion batteries (Table 2).

**Table 2.** Categorization of the thermal management system of batteries[102–108].

Battery cooling system	Power consumption	Passive cooling	
		Active cooling	
	Heat transfer medium	Air cooling	Natural
			Forced
		Liquid cooling	Liquid jacket cooling
			Cold plate cooling
			Mini/Micro channel cooling
			Serpentine channel cooling plates
		Phase change material (PCM) cooling	Liquid-Vapor phase change/refrigerant cooling
	Solid-Liquid phase change		
	Composite PCM		
	Contact between the coolant & battery surface	Direct contact	
		Indirect contact	
	Based on cell configuration	Series	
		Parallel	
		Series+parallel	
		Cross flow	
		Staggered	
	Other techniques	Thermoelectric cooling	
		Heat pipe cooling	Ultra thin heat pipe
Flat heat pipe			
Oscillating heat pipe			
Use water bath& water			
Micro heat pipe array			
Use of hydrogels			
Vortex generator			
Mist cooling			
Hybrid battery cooling systems			

### Air-cooling

One of the natural methods for cooling down the batteries is air-cooling system. The mentioned structure had specific advantages such as low cost, negligible weight, easy maintenance and most important is their simplicity [102,109]. As the natural air-cooling had some disadvantages and drawbacks such as the high temperature working circumstances, the technology of the forced-air with different additions and extra items had structured [110–121].

### Liquid and Refrigerant Cooling

The liquid and refrigerant cooling in a comparison with the air-cooling system has the better thermal performance. Then nowadays it has been using widely as the common technique in various batteries [122]. There are diverse fluids that using for heat transfer directly or indirectly to cool the liquid-based battery systems such as liquid metal, water,

de-ionized water, blend of water and Ethylene glycol, and other divergent fluids [90,123–130].

### PCM Cooling

As phase change materials can absorb the huge quantity of heat, which has generated by Lithium-Ion Batteries has a great capacity to utilize as a cooling technique in battery systems [131]. The introductory of utilizing the PCM's for commercial use had started from the automotive implementation industry [108]. A phase change material is a kind of components that can store the heat and also expel it from the system and is categorized as cost effective and cheap moreover non-corrosive materials [132–135]. In different surveys, researchers demonstrated that cooling with PCM has disadvantages of lower thermal conductivity [136]. There are diverse ways to improve the drawbacks of PCM in cooling such as adding graphite, metal foams, and

**Table 3.** Categorization of the heat pipe [146–150].

Heat pipe based BTMS	
Flat heat pipe	
Flat plate loop heat pipe (FPLHP)	
Ultra thin heat pipe	Ultra thin flat heat pipe
	Ultra thin loop heat pipe(ULHP)
	Ultra thin micro heat pipe (UMHP)
Pulsating heat pipe	
Tube heat pipe	Tube heat pipe with flat evaporator section
	L-shape tube heat pipe with flat evaporator section
	Blended tube heat pipe
Oscillating heat pipe (OHP)	Flexible oscillating heat pipe
Loop heat pipe	
Open-loop flat plate heat pipe	

moreover adding the paraffin to improve the thermal conductivity of PCM [137–139].

### Heat Pipe

Heat pipes are applications, which transfer the heat and are filled with a fluid that evaporates to produce heat [140]. Nowadays heat pipes are widely commercialized in battery packs [122]. The list of merits and benefits of the HP's are so much which some of the emphasized items are great high thermal conductivity, lightweight, reliability, flexibility, low conductivity, volume expansion [141–145]. Table 3 demonstrates the most relevant classification of the heat pipes which has been evaluated and arranged by many scientists [122].

## BATTERY TECHNOLOGY AND APPLICATION AREAS

Electrification is proceeding notably with the common transportation category like any kind of commercial vehicles, buses, cars, railways, aviation, marine and road mobility, moreover; working on the emergency power backup, solar power storage, alarm systems in isolated places and finally portable power packs which empowered and expanded as giant factory -scale production of Lithium-Ion battery automation [151]. Some of the most important factors which affects the commercial vehicle's storage energy are the weight of the battery system and battery management system or basically BMS, battery system performance, cost of the battery, life cycle of the battery, being environment friendly, the power and the energy of the battery, even the most notable is the battery safety. Due to so many researches, LIB's allows the maximum level of energy density [152]. Lithium-ion batteries have various merits such as long life and low self-discharge, furthermore, these batteries have great cycling performances [153]. In the below table, as in table 4 the general application area of the LIB's has been demonstrated.

**Table 4.** Classification of the LIB's utilization [143–145].

The implementation fields of LIB's	Commercial vehicles and road mobility Aviation Marine Emergency power backup Solar energy storage Alarm systems in isolated places Portable power packs
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## CONCLUSION

As a result of the research on Li-ion batteries, the following results were obtained. As the advances in battery technologies, the amount of energy stored by Li-ion batteries increases and important developments occur in control systems. Even more, with the decrease in Li-ion battery prices, it is observed that the usage rate has increased in many areas. It has been observed that the voltage, current, and temperature of the cells commonly affect these batteries. According to the statistics, it has been observed that there is a significant annual increase in the global market values of the Lithium-ion battery from 1992 to 2021.

### Subscripts

GDP	Gross Domestic Product
EV	Electric Vehicle
LIB	Lithium Ion Batteries
TR	Thermal Runaway
PCM	Phase Change Materials
HP	Heat Pipe

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