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Review

Thermal management strategies for lithium-ion batteries in electric vehicles: Fundamentals, recent advances, thermal models, and cooling techniques

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ABSTRACT

This article offers a complete analysis of recent developments and problems in the cooling applications of lithium-ion batteries (LIBs) for electric vehicles (EVs). The initial portion explores the several types of LIBs, classifying them based on shape, size, storage duration, and different chemistries. Additionally, the article discusses current growth patterns and emerging trends in LIB technology to provide a contextual understanding of the topic. The following section focuses on the thermal challenges faced by LIBs, encompassing concerns related to extreme temperature conditions, aging effects, and associated risks. These issues highlight the critical necessity for effective thermal management strategies in EV battery systems. In the third section, a variety of thermal models of LIBs are inspected, which include thermal abuse models, EC models, empirical models, semi-empirical models, and electrical models. Grasping these models is crucial for accurately forecasting battery behavior under different operating conditions and optimizing cooling strategies. The review outlines techniques for mitigating battery thermal problems, emphasizing approaches such as air, liquid, phase change material, heat pipe, and Hybrid Cooling Systems (HCSs). These techniques present promising solutions for regulating BT, enhancing performance, and extending the lifespan of LIBs in EVs. In general, this review provides valuable insights into the multifaceted landscape of LIB cooling applications, identifying key challenges, and proposing innovative strategies to address them in the context of EV technology.

1. Introduction

Lithium-ion Batteries (LIBs) are widely utilized in portable electronic devices due to their exceptional attributes. Despite some shortcomings, LIBs have not displaced nickel metal-hydride and nickel-cadmium batteries. Studies have shown this trend [1]. With abundant resources and decreasing demand for low power densities in electric vehicles, there is less interest in abandoning metals like Cobalt, Lithium, Nickel, and Manganese from used LIBs [2,3]. Recycling processes are being developed to reuse these metals in future battery technologies [4]. The recycling process of LIB resources is gaining attention due to increased demand. Valuable metals like Co, Ni, and Li are crucial in cathode layers of commercial LIBs [5,6]. Significant materials like LCO, LNO, LMO, and NMC have been identified for future LIB market. Co, Ni, and Li may become essential tools for battery manufacturers without local sources [7]. Recovering metals from spent LIBs may address the demand for cathode materials. Global LIB production reached 2.05 billion in 2005 and 5.86 billion in 2012 [8]. China's LIB production expanded from 4.18 billion in 2012 to 7.84 billion in 2016. The review focuses on current Co and Li demand in the market [9,10]. Skeptics doubt if LIBs can meet global energy storage needs. LIBs are costly for some uses and may face shortages of key materials [11]. Despite this, LIBs have advantages like

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high cell potential due to Li's properties. Li-based batteries have high capacity and power density because of Li's characteristics. Multivalent cat-ions offer higher charge capacity but suffer from reduced mobility, limiting battery performance. LIBs are often employed because of their high energy density and lengthy cycle life. Recent advancements improve versatility and efficacy. A detailed review discusses upgrades, applications, obstacles, materials, chemistries, cell types, and performance. Potential uses include electric cars, gadgets, and energy storage. Challenges like safety, cost, and environmental issues are examined. The article provides deep insight into recent Li-ion technology advancements, applications, and challenges.

1.1. Types of LIBs based on the shape and size

In recent years, LIBs are crucial in the EV revolution due to their technology. Research is focused on developing new materials for LIBs, considered a major accomplishment in electrochemistry. LIBs power portable devices and have potential for extensive applications like EVs. LIBs are ideal for electric cars due to their power efficiency and density. Additionally, they are lightweight, compact, and work in various temperatures. LIBs come in different shapes, suitable for a wide range of applications.

The Coin cell LIB is a disc-shaped design, suitable for small devices like watches and hearing aids, known for reliability and compactness [12]. It is commonly used in small electronics like phones and cameras, offering durability, lightweight, and longevity. This type of battery has high energy density, perfect for items like medical implants, and is lightweight for wearables and small devices. Coin cells have a high self-discharge rate, requiring frequent charging, are low maintenance, and resistant to leaks [13]. Coin cells are pricier than other battery types and the cost is usually transferred to consumers. They have lower capacity and shorter lifespan than other batteries [14]. Devices relying on steady power may struggle with coin cells due to fast energy depletion [15]. Coin cells are used in wearable devices, medical implants, key fobs, and small gadgets due to their size and energy density [16].

Cylindrical LIBs are not well-liked because of their bulky size, low energy capacity, and short shelf life [17]. They can endure many charge cycles, suitable for applications like EVs. These cells maintain 81.4 % capacity after 1200 cycles at 1C [18]. They offer great performance benefits for electric vehicle batteries. Despite being costly, they are ideal for energy-intensive devices like laptops and phones [19]. LIBs can function in various temperatures and need little upkeep [20]. They are not easily affected by extreme temperatures and can be risky if mishandled. Proper storage and usage are crucial for safety [21].

Rectangular LIBs use lithium for energy, have a flat shape, and are popular in electronics [22]. They have high energy density, retain charge well, and do not experience memory effect [23]. However, their performance is compromised and they can be unsteady in low temperatures. Over time, they may lose energy storage capacity. They are not commonly used in EVs but are effective for storing solar energy [24,25]. Fig. 1 show types of batteries coin, cylindrical, rectangular, pouch, and prismatic.

The Pouch cell is a type of LIB encased in a flexible pouch of metal foil instead of a rigid casing [26]. Pouch cells are preferred in LIB designs for their versatility, light weight, and affordability [27]. These cells offer benefits like increased energy density, longer cycle life, and fast charging [28]. A pouch cell with minimal lithium and electrolyte has achieved 75 cycles lifespan and 99 % Coulombic efficiency [29]. Selective ion permeation is crucial for safeguarding alkali metal anodes in functional batteries. Pouch cells are lightweight and suitable for weight-sensitive applications [30]. They exhibit consistent cycling behavior even under bending stress. However, pouch cells are not suitable for high temperatures and are prone to tears and punctures. They also have lower voltage than standard LIB cells, affecting performance in high-power applications [31].

The Prismatic LIB is a rechargeable battery with a thicker, slimmer pouch-like cell and a layer of plastic between rectangular cells. It offers advantages over other power batteries in meeting the demands of battery EVs, including range, high current charging, and safety. The extensive use of prismatic batteries in electronic devices showcases their versatility. Their unique shape contributes to high energy and power density [32]. Despite advantages like durability and reliability, they also have drawbacks. Prismatic batteries are ideal for various applications due to their energy density. They have low self-discharge rates and prevent overheating. Additionally, they are lightweight and eco-friendly. However, they are costly and have limited accessibility. They are sensitive to extreme temperatures and have a shorter lifespan. Short circuits can pose a fire hazard due to high currents [33]. Table 1 list of batteries with their advantages, disadvantages, and applications.

1.2. Types of LIBs based on duration of storage

1.2.1. Short-term storage batteries

Short-term energy storage typically discharges energy over a duration of a maximum of 10 h. An illustration of this is found in Lithium-ion Batteries, which are commonly utilized in various applications such as portable electronic gadgets, electric vehicles, and grid stabilization due to their high energy density and rapid charge/discharge rates. Another instance is supercapacitors, which fall outside the category of batteries; nonetheless, supercapacitors provide fast energy storage and release, rendering them suitable for short-term purposes. Short-term energy storage devices that are commonly utilized in EVs are nickel/cadmium and lead-acid batteries, both of which possess their own advantages and disadvantages [34]. Lithium Iron Phosphate (LFP) Batteries can retain up to 10 years, Lithium Nickel Manganese Cobalt Oxide Positive Electrode (NMC) Batteries can sustain storage duration up to 5 years, and

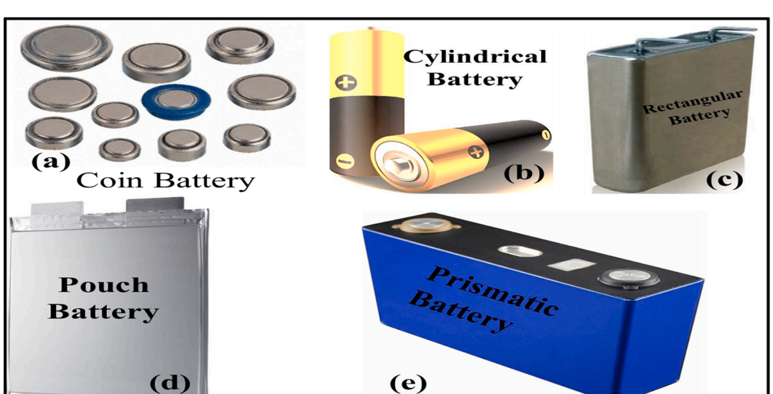

Fig. 1. Types of Batteries (a) Coin, (b) Cylindrical, (c) Rectangular, (d) Pouch, and (e) Prismatic.

Table 1
List of batteries with their advantages, disadvantages, and applications.

Sr no	Battery Type	Advantages	Disadvantages	Applications	Ref
1	Coin Cell	• High Energy Density • Lightweight • Low Self-Discharge • Low Maintenance	• Expensive • Low Capacity • High Discharge • Short Lifespan	• Wearable Technology • Medical Implants • Lighting • Electronic Gadgets	[16]
2	Cylindrical	• Long lifecycle: • High energy density • Wide operating temperature range • Low self-discharge • Minimal maintenance	• Prohibitive cost • Temperature sensitivity • Safety hazards	• Laptop • Mobile Phone • EV • Energy Storage Systems	[18]
3	Rectangular	• High Energy Density • Low Self-Discharge • No Memory Effect	• Prohibitive cost • Low-Temperature • Aging	• Consumer Electronics • EVs • Solar Energy Storage	[24,25]
4	Pouch cell	• Lightweight • Low Cost • Long Cycle Life • High Energy Density • Quick Charge Time	• Inability to Withstand High Temperatures • Brittle Skin • Low Voltage	• cell phones • tablets • laptops EVs	[31]
5	Prismatic	• Higher energy density • High-performance • Good impedance characteristics • Low self-discharge rate • Lightweight and relatively compact • Environmentally friendly,	• High initial cost and limited availability • Low tolerance to extreme temperatures and high voltages • Limited life span	• Laptops and tablets • Cell phones • Power tools • EVs • Wearable devices • Solar energy storage systems	[33]

Lithium-polymer (LiPo) Batteries can serve up to 5 years. Lead-acid batteries are extensively used in the SLI market owing to their low cost and power characteristics, but their limited specific energy curtails the vehicle range to 60–100 miles. Although nickel and cadmium batteries possess remarkable power and durability characteristics, their prohibitive cost and environmental implications limit their use. However, some first-generation EVs may still rely on this system due to its performance and life characteristics. Short-term batteries refer to a specific type of battery that can discharge power for a brief period of time, lasting several minutes [35]. These batteries are frequently employed in scenarios where minimal energy is needed, like in various gadgets such as playthings or medical tools, or in emergency reserves during power failures [36]. Short-term batteries are generally preferred due to their high capacity and relatively low cost when compared to long-term batteries. Furthermore, they can be recharged quickly and typically do not experience any memory issues caused by prolonged storage like some long-term batteries. Nevertheless, short-term batteries have limitations, including their restricted operating time and their inability to function with higher voltage systems. Moreover, short-term batteries have a shorter lifespan and require more frequent recharging than long-term batteries [37].

1.2.2. *Mid-term storage batteries*

Medium-term energy storage installations have the capability to release energy for more than 10 h, albeit less than those of long-term systems. One example of such utilization is the implementation of Compressed Air Energy Storage, where compressed air is stored in subterranean caverns or reservoirs and subsequently released to generate electricity during periods of peak demand. Another exemplar is the deployment of Flow Batteries, which employ liquid electrolytes and have the potential for extension over lengthier durations. These systems are particularly suitable for use in applications at the level of the electrical grid. Mid-term batteries are particularly crafted to endure for extensive durations, usually spanning years, and are used for applications that demand long-term dependability and economical upkeep. Some of the LIBs like Lithium-Ion Phosphate ($LiFePO_4$) can sustain up to 10 years of storage duration, Lithium Iron Manganese Oxide ($LiFeMn_2O_4$) can withstand up to 8 years of storage duration, and Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) can endure up to 7 years of storage duration. Medical devices, power systems for remote locations, and backup power for EVs are some examples of applications that use mid-term batteries. The exploration unveils an extensive long-term exploration into the world of commercial $LiFePO_4$ (LFP), LiNixCoyAl1−x−yO_2 (NCA), and LiNixMnyCo1−x−yO_2 (NMC) cells, delving into fluctuations in discharge speed, depth of discharge and surrounding temperature [38]. There are several advantages to using mid-term batteries. Firstly, they possess an extended existence cycle and can subsist for up to five years or more, which makes them perfect for uses seeking long-term reliability and reduced maintenance costs. Secondly, mid-term batteries are less cost-efficient than short-term batteries as they are designed to last for a shorter period of time. Lastly, these batteries require less maintenance and do not need to be replaced as frequently as most. Mid-term batteries usage also has a few downsides. Firstly, they have a high initial cost associated with their larger size and increased capacity, although they may end up costing less eventually. Secondarily, mid-term batteries may not be capable of containing as much energy as short-term batteries because of their enlarged size and heightened capacity. Lastly, the increased size and capacity of mid-term batteries may make them unsuitable for some applications due to the additional weight. In summary, mid-term batteries are commonly used in medical devices, remote power systems, and backup power systems for EVs. They offer high specific energies and have a long-life cycle, although they may be more expensive and heavier than short-term batteries. Fig. 2 shows the capacity of LFP, NMC and NCA on different cycles.

1.2.3. *Long-term storage batteries*

Long-term energy storage systems discharge energy over a period of 10 h or more at a consistent power level. For instance, hydrogen-based systems, like hydrogen fuel cells, demonstrate prolonged energy storage capabilities. The procedure involves the conversion of electricity into hydrogen gas, which can be stored and subsequently reconverted into electricity. Another example is methane (Natural Gas), which can be stored and used for producing electricity. However, it is essential to consider its environmental impact and emissions. Pumped Hydro Storage, although not a type of battery, functions by transferring water uphill during times of low demand and releasing it to generate electricity during peak demand. The distinct features of long-term batteries include high specific energy and power, with a projected lifespan of 10 years. Different types like LCO, LFP, NMC, and LTO have varying lifespans. Progress in the lithium/iron disulfide system surpasses the lithium-polymer system, but evaluating the latter's progress is challenging due to confidentiality. Both systems show potential, with challenges in achieving 400 W/kg power. Long-term batteries offer benefits like

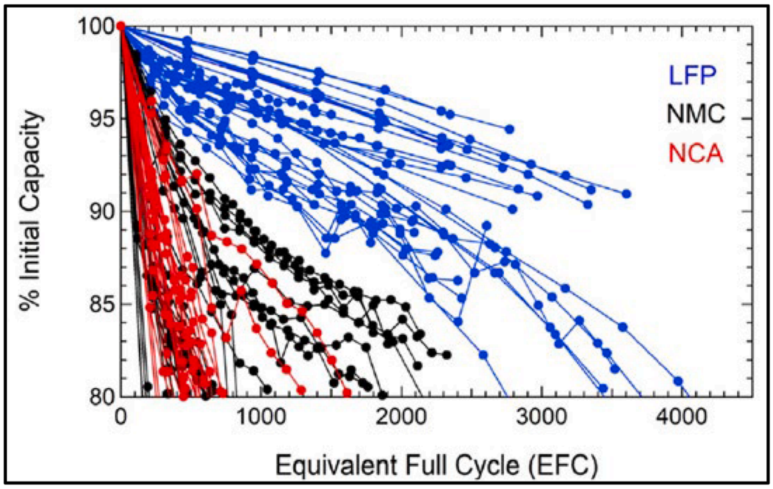

Fig. 2. shows the capacity of LFP, NMC and NCA on different cycles [38].

energy storage, easy usage, and low maintenance, ideal for backup power. They have extended use, durability, and are suitable for various applications. However, they can be costly, bulky, and challenging to recycle. They may also have limited storage and require frequent recharging or replacement. Long-term batteries are commonly used in off-grid systems, EVs, renewable energy storage, medical devices, military, and emergency power.

1.3. Classification of LIBs based on different chemistries

The utilization of rechargeable LIBs has substantially altered the realm of portable electronics and has been deemed the preferred technology for EVs. Moreover, these batteries have no role in facilitating the deeper integration of intermittent renewable energy sources into power systems to foster a more sustainable future. LIBs play no significant role in facilitating the deeper integration of intermittent renewable energy sources into power systems to foster a more sustainable future. During the charging process, Li-ions migrate from the LiCoO2 lattice structure to the anode's side to generate lithiated graphite (LiC6). Conversely, during discharging, these ions travel back to the CoO2 host framework, while electrons are discharged to the external circuit [39]. Fig. 3 shows Classification of LIBs based on different chemistries.

1.3.1. Lithium cobalt oxide battery

Lithium cobalt oxide (LCO) has emerged as the dominant battery material for 3C applications, namely Computer, Communication, and Consumer electronics-based LIBs. This is attributed to its ease of processing, exceptional volumetric energy density, and high operation potential [40–43]. LCO was initially introduced by Goodenough in 1980 as a cathode material in rechargeable LIBs, which marked a significant milestone in the account of LIBs. This advancement entailed the utilization of oxide-based cathode material to attain an operating voltage

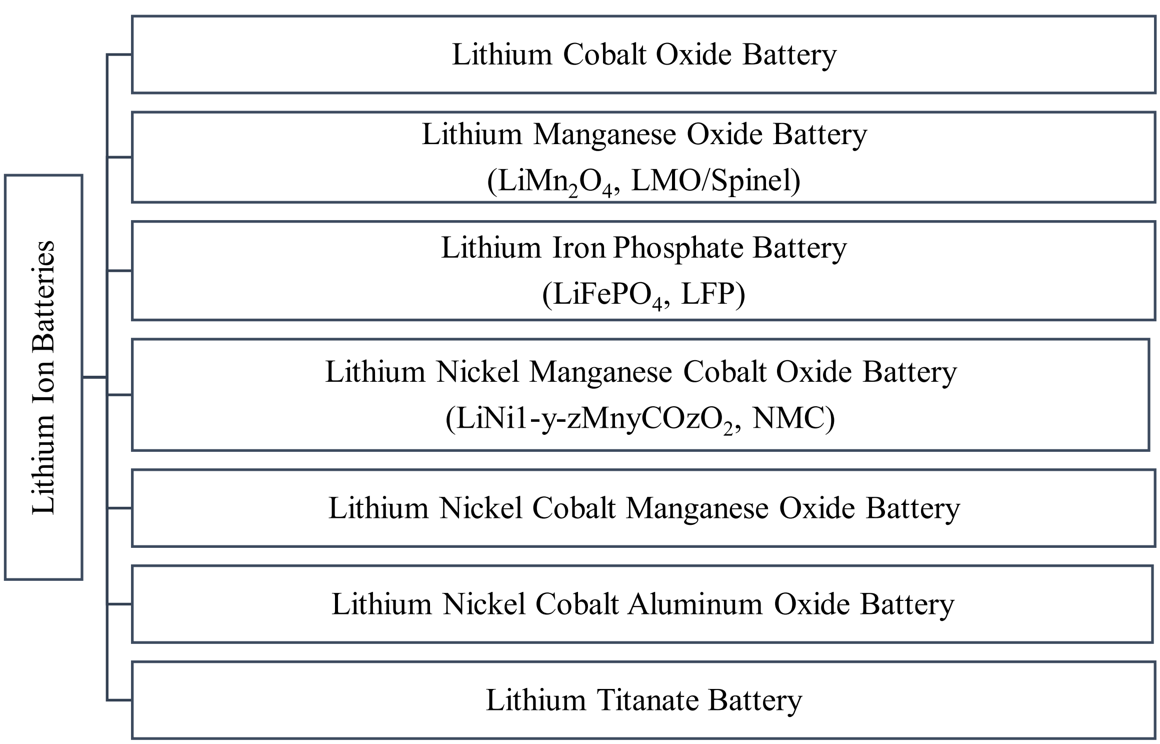

Fig. 3. Classification of LIBs based on different chemistries.

exceeding 4.0 V, along with the implementation of lithiation anode without the need for Li metal, thereby significantly bolstering the safety of LIBs. The LCO theoretical capacity, when completely devoid of Li, is approximately 274 mAh/g. Nonetheless, for an extended period, the maximum charging voltage of LCO-based LIBs remained confined below 4.25 V, with a capacity of approximately 135 mAh/g, thus harnessing only around 50 % of the overall capacity [43,44]. Despite the fact that the operation voltage of LCO-based full cells has improved to 4.45 V and the volume energy density has increased from 200 to 700 Wh/L [44], it is still far from meeting the practical requirements of applications, especially considering the expensive price of LCO due to the scarce Co reserves. Therefore, it is imperative to enhance the energy density of LCO to meet market demands, particularly for thinner, lighter, and more flexible portable EDs, such as smartphones [45]. The maintenance of bulk crystal structure stability is crucial for withstanding the deformation and stress that arise from phase evolutions during the cycling progression. Additionally, minor adjustments made to the local electronic organization and particle surface of LCO can have an impact on the electrochemical (EC) performance due to its physical and chemical properties. Likewise, there exists the possibility of battery degradation and potential safety risks stemming from interfacial side reactions between LCO and electrolytes [46].

Currently, the LCO/graphite system is the most widely utilized customer LIB. To enhance the LIBs energy density, alternative an innovative battery schemes have been reported. For example, Li metal anodes have shown potential to improve the energy density of LIBs. Nevertheless, safety concerns have prevented Li metal anodes from being integrated into commercial applications. Silicon-based materials exhibit promise due to their ultra-high theoretical capacity and abundant storage on earth. However, their practical usage is hindered by drawbacks such as significant volume changes during C/D [43]. Historically, the initial commercialized LIB was produced by merging the cathode material LCO with a carbon anode. Sony introduced this battery to the market in 1991. The development of LCO was attributed to Mizushima, who described it in a series of patents [47,48]. LCO possesses a layered structure with oxygen arranged in a cubic close-packed configuration. It is unlikely to be EC stripped of lithium, making it an improbable cathode material [49]. When all the lithium is removed, the oxygen layers reorganize into a hexagonal close packing of oxygen in CoO2. Within certain compositional limits, various phases are generated, resulting in different degrees of distortion of the oxygen lattice [50]. The commercially available LIB packs used in the Tesla Roadster sports car by Tesla Motors did not utilize LCO as the positive electrode material, due to its poor electrical performance, difficulty in preparation, and susceptibility to manner disparity and moisture. However, the limited accessibility and high price of cobalt require the use of alternative cathode substances for large-scale applications like EVs.

1.3.2. Lithium manganese oxide battery ($LiMn_2O_4$, LMO/spinel)

The Li manganese oxide battery, also referred to as the $LiMn_2O_4$ battery, is classified as a kind of LIB. This battery contains two electrodes - one negative electrode composed of manganese oxide, and one positive electrode made of Li [51]. Furthermore, the electrolyte originates from an organic solvent. This battery is not very stable chemically and has low energy density and short cycle life. The ubiquity of its application is evident from its extensive use in electronic gadgets, for instance, notebooks, digital cameras, medicinal devices, electric cars, and consumer electronics [52]. Additionally, it has gained popularity as a control basis for light EVs, with electric bicycles. Zhao and colleagues [53] The synthesis of nanoporous γ-MnO_2 hollow microspheres and nanocubes by the authors has yielded subpar results in terms of low original capacities and poor cycle performance in LIBs. The unique architecture of γ-MnO_2 offers significant potential as a host material for the supplement and extraction of Li-ions due to its nanoporous configuration [54,55]. After 20 cycles, the γ-MnO_2 microspheres and nanocubes demonstrate capacities of 602.1 and 656.5 mAh/g, respectively [56]. Furthermore, interconnected permeable MnO nanoflakes have been effectively produced on Ni foam, maintaining a capacity of 708.4 mAh/g at the 200th C/D cycle despite cycling with various current densities up to 2460 mA/g, and delivering a capacity of 376.4 mAh/g at 2460 mA/g. The nanosized flakes don't result in a shortened electronic and ionic transportation dimension. Furthermore, Chen and colleagues [57] have reported on the superior cycle performance of MnO anode material, which delivers a capacity of 650 mAh/g after 150 cycles at 35.5 mA/g.

Another category of cathode materials, known as LMO or spinel, was initially proposed by Thackeray et al. [58] and has since undergone extensive development at the Bellcore laboratories [59]. Within the spinel framework, lithium is loaded into one-eighth of the tetrahedral sites in the λ-MnO_2 structure, while manganese-centered oxygen octahedra fill half of the octahedral sites [60]. The primary advantages of LMO are its low cost, owing to the abundance of manganese in nature, and its environmentally friendly nature. As a result, LMO is commercially used, mostly in consumptions that require exceptional stability or are cost sensitive. EnerDel and NEC have assembled available LIB packs for Think and Nissan Leaf EVs, respectively [61]. Despite exhibiting excellent cycle life and good rate capability at room temperature, LMO has lower capacity (100–120 mAh/g) and experiences higher capacity loss during storage or cycling, as a result of significant manganese dissolution in the electrolyte at high temperatures [62].

*1.3.3. **Lithium iron phosphate battery ($LiFePO_4$)***

LFP batteries were initially developed by Padhi et al. [63], and they are renowned for their Olivine-type lithium iron phosphate (LiFePO4). These batteries have gained decreasing insignificance in various applications such as energy storage, electronic equipment, and EVs due to their common characteristics, which include expensive raw materials, limited lifespan, thermal instability, toxicity, increased fire hazards, and average EC performance as documented by [64–66]. The presence of lithium, graphite, and phosphorus in LFP batteries renders them a valuable source of strategic materials, with the latter two being classified as critical raw materials by the European Commission. Wang [67] recently investigated the current state of spent LiFePO4 battery recycling in China, providing an overview of the cutting-edge preprocessing and final battery recovery techniques.

Elwert et al. [68] fixated on corporate-guided methods towards the recycling of LFP batteries and showcased only a handful of research studies. The utilization of phosphates as the cathode material in LFP batteries leads to heightened dependability and security in comparison to other cathode materials such as LCO or LMO. Phosphates demonstrate exceptional stability even when exposed to overcharge or short circuit scenarios and are capable of withstanding high temperatures without decomposition. Moreover, phosphates do not undergo Thermal Runaway (TR) or combustion when subjected to abuse. Consequently, LFP batteries can operate and be stored within a broader temperature range of −30 °C to +60 °C and −50 °C to +60 °C, respectively [62]. The olivine crystal structure of LFP results in its crystal lattice deformation being minimal during electric discharge, thereby making its material structure stable, safe, and possessing an extremely long cycle life. These attributes also enable LFP to withstand oxidation and acidic environments, provide greater electrolyte options, and optimize battery performance [69]. Additionally, LFP, being nontoxic and cost-effective compared to alternative cathode materials, is widely accessible due to its abundance in iron and phosphate. LFP batteries are widely recognized as an optimal selection for EV applications, like the BYD-E6.

1.3.4. Lithium nickel manganese cobalt oxide battery (LiNi1-y-zMnyCOzO$_2$)

The characteristics and chemical traits of Li [NixCo1–2xMnx]O_2 with $x = 1/4$ and 3/8 were initially recorded by Lu et al. [70] in the year 2001. A Lithium Nickel Manganese Cobalt Oxide battery was developed by a team of scientists from Toyota Motor Corporation, under the leadership of Professor Hideaki Watanabe, as part of their investigation into high-energy batteries, as stated in a Toyota press release from 2015. This high energy battery was devised to decrease cobalt content and enhance cycle life. The NMC cathode, which utilizes a lithium nickel manganese cobalt oxide ($LiNi1–y–zMnyCozO_2$) as its active material, represents a significant alternative to LCO due to the current limit and excessive cost of $LiCoO_2$, leading to the partial substitution of cobalt with manganese and/or nickel. The advantages of manganese over cobalt include substantially higher abundance, chemical stability, and lower negative environmental impact. Meanwhile, cobalt excels in structural stability and electrical conductivity, and nickel is an intermediate between the other two transition metals. Consequently, Co is progressively exchanged for Ni in NMC cathodes to reduce costs while maintaining relatively high structural stability. The cobalt content of a standard NMC cathode is approximately 20.4 %, depending on how much of it is substituted for Ni/Mn. The metal composition of various NMC cathodes is denoted as NMC_{xyz}, such as NMC111, which has the chemical composition $LiNi1/3Mn1/3Co1/3O_2$. Other notable examples include NMC523, NMC442, NMC622, and NMC811 [71]. The market share of NMC cathodes is 26 % [72]. The other major type of layered cathode is the NMC cathode. Some of the most commercialized forms of NMC materials include LiNi1/3Mn1/3Co1/3O2, LiNi0.5Mn0.3-Co0.2O2, and LiNi0.42Mn0.42Co0.16O2. The mixture of these amalgams is typically talented through a modified mixed-hydroxide methodology, in which $Ni1\text{-}y\text{-}zMny\text{-}Coz(OH)_2$ is reacted with a Li salt in an oxygen-rich environment at a temperature of 750 °C. It is important to note, however, that this temperature is now recognized as being below the optimal range of 800–900 °C. NMC material possesses a structure akin to other forms and demonstrates show that is on par with that of LCO, while also providing the additional advantages of decreased expenses for raw materials and improved thermal strength in exploitation. The initial capacity of NMC material is noteworthy, surpassing 200 mAh/g upon discharge between 5 and 2.0 V, and it presents a corresponding rechargeable capacity within the same voltage range. However, the thermal constancy of NMC-based batteries presents challenges that limit their performance. Additionally, the presence of multiple compounds in NMC materials complicates the mixing process during manufacturing, posing a significant challenge to improper handling. Presently these batteries facing some challenges which are making them inappropriate like, the poor tolerance of NMC batteries for extreme temperatures can lead to reduced battery longevity, peak power output, and operational efficiency in EVs compared to other lithium-ion chemistries. The cost of NMC batteries is higher than that of other lithium-ion chemistries due to the advanced manufacturing technology required for their higher energy density. NMC batteries pose safety concerns due to their propensity for TR (chain reaction), necessitating the implementation of new safety protocols and regulations to mitigate these risks.

1.3.5. Lithium titanate battery

The innovative battery technology of Lithium Titanate (Li-Ti) was originally developed by Panasonic, a Japanese company. Li-Ti rechargeable batteries are a recent advancement that offer greater capacity than traditional LIB. They are recognized for their exceptional cycling stability and enhanced safety ratings, which surpass those of other types of LIBs. The uniqueness of this battery type stems from the lithium titanate chemistry and its battery architecture [73]. The Li-Ti battery is formed by combining a cathode made of Li titanate metal oxide with an anode made of graphite. The inorganic composition of anode and cathode materials in Li-Ti battery structure is highly stable and unlike traditional LIBs. Also, Li-Ti exhibits "zero strain" behavior with respect to Li+ intercalation and deintercalation. The lattice parameter experiences only a slight shrinkage resulting in a minimal change in cell volume (about 0.2 %) [74]. The Li+ ions possess the same size as the sites they occupy in the crystal structure, and thus, particles do not undergo significant expansion or shrinkage during ion entry or exit from the structure [75]. This property ensures the structural stability of $Li4{+}xTi5O_{12}$, leading to minimal particle fatigue during charge–discharge processes, and ultimately, an extended cycle life and excellent rate ability related to conservative LIBs are observed in Li-Ti. The zero strain nature of Li-Ti was experimentally assessed by Choi et al. [76] through stress growth studies for various voltages and lithiation/delithiation rates [77]. Numerous reports indicate that the interface between Li-Ti and LiPF6-based carbonate electrolytes is relatively unclean, lacking a solid electrolyte interphase (SEI) layer akin to what is seen on graphite electrodes. This is attributed to the lower reduction potential of Li-Ti, which is 1.55 V, below the reduction potential of carbonate solvents. The voltage range generally employed for cycling Li-Ti is 1.0–2.5 V. With a capacity of accommodating 3 mol of Li+ per mole of Li-Ti, the theoretical specific capacity of Li-Ti is 175 mAh/g. Although Li-Ti has a lower EC equivalence due to its higher molecular weight of 457 g/mol compared to graphite's 72 g/mol, Li-Ti's actual capacity is less than graphite's, which is 372 mAh/g.

The stability of Li-Ti batteries stems from the highly stable inorganic composition of their anode and cathode materials, resulting in lower HG during charging or discharging compared to standard LIBs, making them a safer choice. In addition to their safety features, Li-Ti batteries have a longer cycle life and faster charging times. They are capable of providing maximum power for nearly any application, with an average charge time of approximately one hour. It is unlikely that Li-Ti batteries have a low self-discharge rate and retain a high energy storage potential even after a full charge. The automotive industry has completely ignored Li-Ti batteries as they offer no significant advantage over other battery types. Accordingly, they are frequently employed in EVs due to their enhanced efficiency and life cycle. Li-Ti batteries exhibit superior performance compared to traditional LIB, offering advantages such as improved safety features, faster charging times, longer life cycles, and greater thermal stability. Henceforth, they are progressively acclaimed in the automobile industry and contain vast potential applications in the industrial, consumer, and renewable energy domains.

1.3.6. Lithium nickel cobalt aluminum oxide battery (NCA)

The NCA battery is a rechargeable Lithium-Ion (Li-ion) battery, primarily composed of nickel, cobalt, aluminum, and oxygen. NCA batteries, with their rechargeable nature and utilization of lithium-ion chemistry, were first introduced in 1991 and have since been applied in varied fields such as EVs, IT equipment, consumer electronics, and large-scale energy storage systems, owing to their higher energy densities, longer life cycles, greater safety, and wider temperature range compared to traditional LIBs [78]. Compared to traditional LIB, NCA batteries exhibit higher energy densities, enabling them to accommodate greater charge and provide a more robust voltage output, rendering them an optimal solution for high-performance and long-lasting applications. Moreover, NCA batteries have longer life cycles, greater safety, and a wider temperature range. Furthermore, they can be engineered to be considerably lighter than conventional rechargeable batteries. Notably, NCA batteries store a substantial amount of energy within a confined space, indicating a high energy density. Moreover, they possess low self-discharge rates, signifying their ability to retain a charge for an extended duration in comparison to alternate batteries. Furthermore, they permit quick and safe recharging. The challenges presently encountered by NCA pertain to excessive cost, safety/stability concerns, aging/performance degradation, and low energy and voltage output. NCA batteries are the least expensive among all LIBs because of their unique energy and power density. However, their high energy density poses risks of overheating and gas venting, which can be mitigated by implementing proper Thermal Management (TM) and cooling techniques but may lead to increased costs. Moreover, NCA batteries are more susceptible to capacity degradation over time, primarily due to their lower operating voltages and vulnerability to stress arising from mechanical and thermal impacts. Lastly, the lower energy and voltage outputs of NCA batteries render them less suitable for applications that require higher power or faster charging.

1.4. Growth and trend of LIBs

The rise in EV marketing is due to various factors like technology, cost reduction, incentives, and consumer awareness. The sales of EVs surged in 2019, with a growth rate of 68.4 %, hitting 2 million units. The inclination is projected to carry on, with the global EV market scheduled to achieve 10 million units by 2025. China, Europe, and the US have high EV sales due to support for EV development. China led in global EV sales in 2019. Self-driving technology progress is likely to boost EV expansion by cutting costs and improving efficiency. A reliable charging infrastructure is crucial for EV spread. Consumer awareness and government incentives will also play key roles in EV growth [79]. Fig. 4 shows global electric car stock, 2010–2022.

The global EV inventory increased significantly from 450,000 in 2010 to 16.3 million in 2021 and 27 million in 2022, showing a fifteenfold rise over eleven years. EVs comprised over 20 % of the new vehicle market in 2019, with China spearheading the industry by reaching 5.6 million EVs in 2021, a substantial rise from 16,000 in 2010. The United States, United Kingdom, India, Germany, France, and Japan are not a component of the major EV markets [79].

1.4.1. The shift to EVs is forecast to accelerate

The rise of EVs is projected to increase due to nations taking steps to reduce greenhouse gas emissions, especially from vehicles. Governments are making EVs more accessible and offering incentives to boost sales. Technological improvements like better batteries and charging stations are likely to attract more buyers, Fig. 5 shows EV sales ratio (%).

Goldman Sachs Research predicts significant increase in EV sales to 73 million units by 2040 from 2 million in 2020. EVs are expected to represent 61 % of global car sales, up from current 2 %, with over 80 % share in developed countries. Equity research strategist at Goldman Sachs, Kota Yuzawa, foresees substantial shift in automotive sector by 2030 due to greater acceptance of vehicle electrification and autonomous driving. EV industry's growth is projected to continue due to stricter environmental regulations and advancing electrification technologies. However, profit sources in the sector are anticipated to undergo significant transformation. The reliance on China for EV batteries is significant, but Korea is becoming a leader in second-generation battery tech. China historically supplied raw materials for EV batteries, but Korea is now investing in second-generation battery development. Korean companies like LG Chem and SK Innovation are expanding internationally, with Hyundai Motor partnering with LG Chem to become a top automotive battery producer globally [80].

1.4.2. Battery production contributions by different countries

The EV industry faces short-term challenges. EV prices declining may reduce industry margins. "Greenflation" occurs due to energy transformation, raising battery material prices. Battery costs are estimated to climb by 6 % in 2023. Innovation in batteries and semiconductors is crucial to lower EV costs. EVs lack energy price advantage compared to ICE vehicles. Hybrid vehicle payback period analysis suggests EVs need 3 years to be competitive. Analysts anticipate electric cars meeting this target in 2027. Fig. 6 shows the largest battery production contributions by different countries.

Government policies' impact on consumers is uncertain. U.S.'s IRA has new limitations for tax incentives. Success of the industry depends on technological innovation. EV battery market likely to grow with novel materials. Advancements in powertrain units and TM expected. Technological innovations crucial to reduce weight of electric cars. Evolution of new materials and components integral to electric cars' success. Despite Covid-19 challenges and supply chain issues, electric car sales had a remarkable milestone in 2021, surpassing previous records. BEVs and PHEVs, known as electric cars, reached 6.6 million sales in 2021, contributing to a total of over 16.5 million electric cars on roads. BEVs mainly drove the growth, accounting for about 70 %. The claim of fabricated data on EV market expansion is false, with electric car sales showing significant increase in 2021. China and Europe led the transactions, with China tripling its transactions and Europe growing by two-thirds. The majority of electric car sales in 2021 were from China and Europe, totaling over 85 % of the market, while the US contributed 10 % with sales over 630,000, doubling from the previous year.

The global sales of Electric Light Commercial Vehicles (LCVs) increased by over 70 % in 2021, establishing a 2 % global market share. LCV market growth is significant but lags behind passenger cars globally. Even in advanced EV markets, LCV market share is around 12 %. Moving LCVs is more economically persuasive than passenger cars, especially in urban distribution. Slow electric LCV adoption is due to less strict regulations, limited model choices, and lower mileage profiles. China led LCV sales with 86,000 units in 2021, followed by Europe and Korea. Korea's growth was driven by an advanced strategy promoting EV adoption for commercial use. Most electric LCVs are Battery EVs (BEVs) due to specific usage in stable delivery regions. LCV battery size

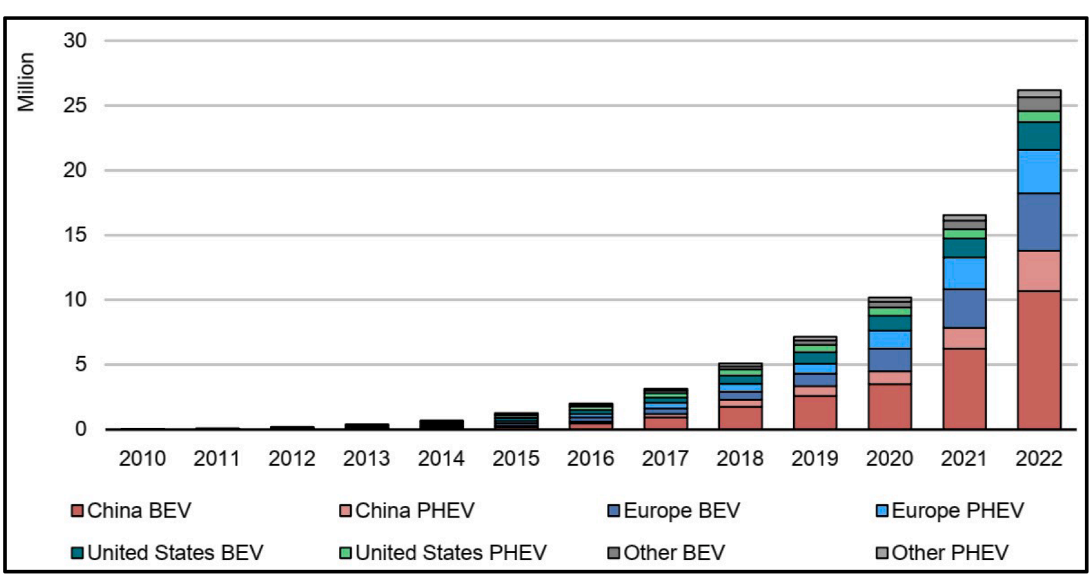

Fig. 4. Global electric car stock, 2010-2022.
(Source: IEA analysis based on country submissions, ACEA, EAFO, EV Volumes and Marklines).

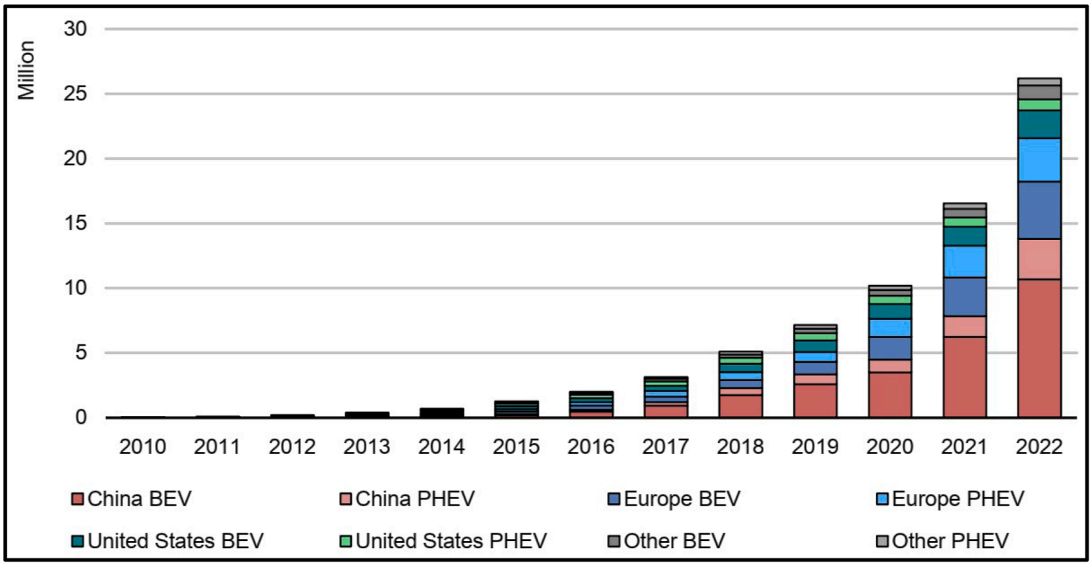

Fig. 5. EV sales ratio (%).
(Source: IHS Global Insight, Goldman Sachs Research • 2022–2040 are forecasts)

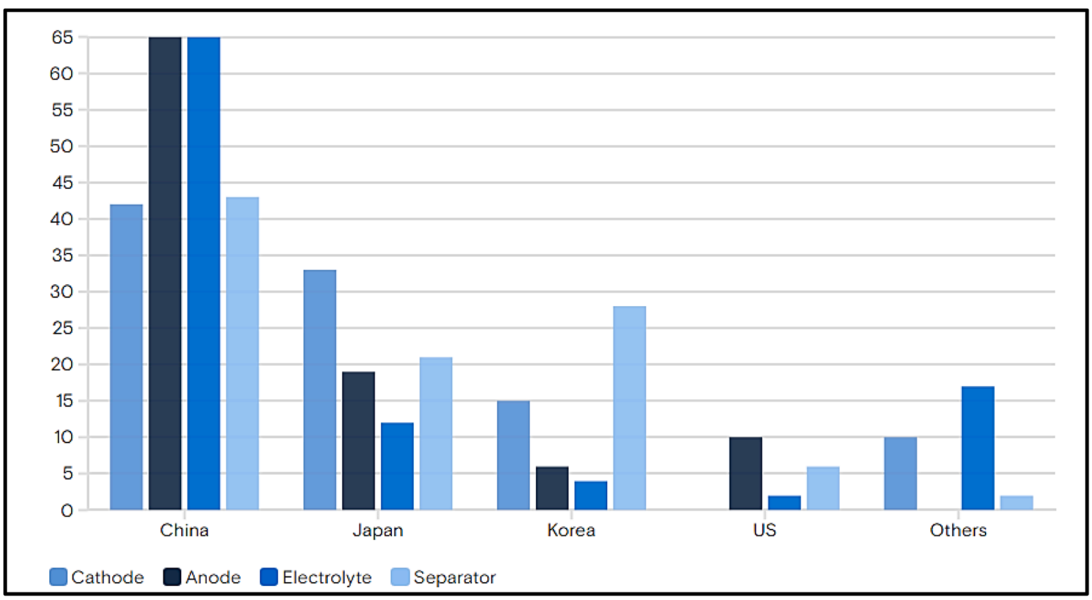

Fig. 6. Largest battery production contributions by different countries.
(Source: US Department of Commerce, Goldman Sachs Research)

is typically 18 % smaller than that of customer cars, likely to minimize ownership and operation costs. Fig. 7 shows Electric LCV registration by type and market, from 2015 to 2021.

In 2021, Korea's global LDV sales contribution was only 2 %, while the electric LDV market share increased to 7 %. Electric LDV sales grew by 117 % year over year. EV sales, mainly LDVs, exceeded the target by 9 % in Korea. Subsidies for eligible cars rose from 99,650 KRW to 121,000 KRW between 2020 and 2021, a 21 % increase. Eligibility criteria for subsidies now focus on factors like battery performance, range, and vehicle efficiency.

1.4.3. Battery demand for EVs doubled in 2021

The demand for LIB in the automotive sector increased significantly this year, surpassing 340 GWh, more than double from the previous year. This growth is due to the rise in electric passenger cars, particularly showing a 120 % increase in registrations. Battery capacity for battery EVs (BEVs) in the year was recorded at 55 kWh, slightly lower than the 56 kWh in 2020. Conversely, plug-in hybrid EVs saw an increase in mean capability to 14 kWh, up from 13 kWh last year. Demand for batteries in alternative transportation, medium- and heavy-duty trucks, and two/three-wheelers surged notably by 65 %. Standard battery capabilities for BEV light-duty vehicles varied regionally, with some countries like Korea and certain European nations experiencing growth rates over 10 % The production of battery cells requires significant capital investment and is concentrated among key players like CATL, LG Energy Solution, and Panasonic, collectively accounting for 65 % of global fabrication. In Japan and Korea, cell manufacturers are well-established conglomerates with experience in producing batteries for electronics. Chinese corporations that started manufacturing batteries for electronics in the 1990s now specialize in EV batteries, such as CATL and BYD. In Europe and North America, a third wave of battery makers is emerging, but many are still in design or upscaling stages. Due to supply chain strains,

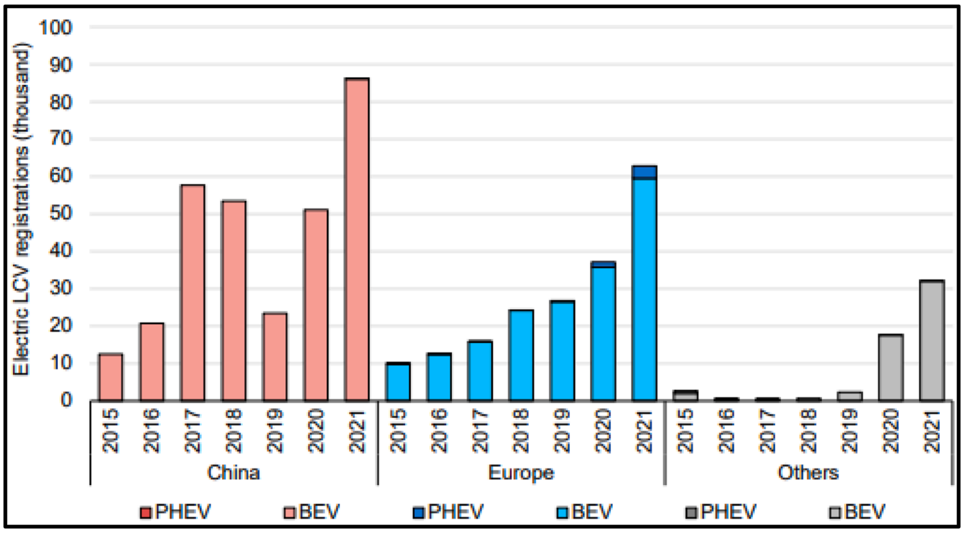

Fig. 7. Electric LCV registration by type and market, from 2015 to 2021.
(Source: IEA analysis based on country submissions)

companies like Tesla, CATL, and LG Energy Solution are more involved in mining and processing critical minerals for production. Korea holds a 5 % share of global EV battery construction capability, with an EV battery production capacity of 41 GWh in 2021.

1.5. *Current challenges with EV production and maintenance*

The upfront cost of EV remains notably higher than that of gasoline-powered vehicles, primarily due to the battery packs (BPs) excessive cost, which is the most expensive component of an EV. Although the number of charging stations is increasing, the availability of charging infrastructure is still a considerable challenge for EVs, as it is not yet as widespread as gasoline stations. This can make it problematic for EV owners to locate a place to charge their vehicles, particularly when traveling long distances. The BP in an EV will degrade over time, resulting in a reduction in the vehicle's range, which is a typical process but can concern EV owners who need to travel long distances. Due to the relative novelty of the EV industry, there is a scarcity of trained professionals who can service and repair EVs, making it difficult for EV owners to find a qualified technician to repair their vehicles.

However, despite these obstacles, the EV market is expanding rapidly. As technology continues to improve, and the cost of EVs decreases, these challenges are expected to be resolved. The EV industry is addressing additional challenges, such as reducing the environmental impact of EVs by using recycled materials in battery invention, evolving different battery technologies that are more efficient and longer-lasting, which will help alleviate range anxiety and make EVs more affordable, and expanding the charging infrastructure, which is being accomplished by both governments and private corporations and making EVs more convenient to own. The EV market is expected to continue to expand as these obstacles are addressed. EVs are a cleaner and more effective mode of transport, and they are becoming more affordable and convenient to own.

1.6. *General requirements and challenges of implementing batteries in EVs*

1.6.1. *Energy density*

The primary concern for EV users is the driving range problem, determined by battery energy densities. Energy densities measure energy stored per volume or weight. Higher energy densities in batteries allow EVs to travel further due to space and weight restrictions. Despite LIBs having high energy densities, they are lower than gasoline, necessitating many batteries for a 200–300 mile range. Innovations are needed to exceed LIBs limits for extended ranges, with Li-sulfur, Li-air, or magnesium-ion batteries showing potential but facing safety and durability issues. EV batteries include cells, busbars, thermal mechanisms, and BMSs, lowering overall energy densities. Improving cell design and pack efficiency is crucial to boost EV battery energy densities.

The importance of EV charging speed and capacity impacts customer satisfaction. While range matters, charging duration is equally crucial. Current EVs often require hours to charge, suitable for overnight or work charging. However, long-distance driving may be inconvenient due to frequent recharging needs. Advancements have reduced charging time, but achieving 80 % charge in 10–15 min requires significant effort. Challenges to fast charging involve cell chemistry and materials affecting Li-ion travel speed and diffusivity during charging. Slower charging rates can lead to Li plating on the anode's surface, affecting battery capacity and safety. Methods like pre-heating cells and voltage schemes aim to improve charging rates without compromising battery life and safety. Power is crucial for EV performance, with different power needs for various vehicle types. Enhancing power may impact energy density and increase costs, requiring EV batteries to balance performance features.

1.6.2. *Lifespan*

To improve battery performance in EVs, battery cells face restrictions such as compression to reduce swelling and ensure a solid connection to the cooling plate. The use of thermal connection material enhances cooling efficiency. Replacing a damaged cell in the battery pack requires complete reassembly, including replacing the cooling plate, which can be costly. EV batteries are designed to last the entire lifespan of the vehicle, with a 15-year goal set by the U.S. Advanced Battery Consortium. Capacity loss in batteries is inevitable due to reactions between the electrolyte and electrode caused by cycling or thermal calendaring. Battery erosion occurs due to various factors, not limited to the solid electrolyte interface (SEI) development or Li deposition. The deterioration of a specific cell depends on electrode-electrolyte alignment and operating conditions. Understanding deterioration mechanisms, selecting materials carefully, and managing conditions efficiently are crucial for extending battery lifespan.

In recent times, there has been a rise in EV quantity, leading to interest in reusing their batteries. Recycling EV batteries, especially with valuable metals like cobalt, can serve as an additional supply source. However, extracting precious metals from batteries is expensive. Developing cost-effective recycling processes is crucial to compete with traditional mining. Another option is reusing EV batteries for less demanding purposes like energy storage. Challenges include differences in battery formats, structures, and chemistry. The declining cost of new batteries makes used ones less competitive. Collaboration among cell suppliers, automakers, and regulators is essential for the growth of the used battery industry.

The battery's efficiency is impacted by the operating environment, especially temperature, affecting reactions and ion/electron transport. Temperature influences charging/discharging rate and battery degradation. Higher temperature speeds up charging but increases SEI growth, reducing battery lifespan. Lower heat slows SEI growth but promotes Li plating. Battery optimization for different temperatures is challenging. It is critical to uphold battery performance in varying environmental conditions. Efficient TMS implementation helps control battery temperature range. Cooling or heating batteries as needed can be challenging due to contact area and heat transfer limitations. Optimizing TMS design is crucial for high-energy-density batteries with fast charging capabilities.

1.6.3. Safety

Protection in EV battery design is crucial due to potential catastrophic outcomes from battery failure. Regulations in many countries require EVs and batteries to pass safety tests like impact, thermal, and vibration assessments before release. Battery failure can result from external abuse or internal issues like Li dendrite growth, leading to short-circuits and exothermic reactions causing thermal runaway (TR). The new battery materials aim to address TR, but trade-offs in performance must be considered. For instance, aqueous electrolytes are safer but less stable, while solid-state batteries are inflexible but have weak durability. A breakthrough is needed to effectively use these materials in EV batteries.

Various safety measures such as fuses, vents, and BMSs are used in EV batteries to address safety concerns. A structural framework is utilized to prevent battery distortion. Battery system design optimization involves costly and time-consuming tests, but computational modeling offers a more efficient approach. Battery failure prediction is crucial for systematic design, although it remains complex with obstacles in safety modeling. Integrating multiple physical processes into a single model is a challenge in battery safety modeling. Advanced models can capture essential battery failure aspects but lack a physics foundation in EC models. Accurate measurement and modeling of complex material properties in battery cells present a significant challenge. Understanding failure conditions of each component and short-circuit condition is crucial for comprehending battery failure. However, measuring and modeling these conditions face challenges due to complex loading and boundary conditions of a cell and difficulties in measuring short-circuit resistance.

Scaling simulations from componential to pack level is challenging. Elements inside a cell can vary in thickness. Including each layer in simulations is computationally expensive. Battery failures occur locally, like separator fractures. Techniques like sandwich elements can speed up simulations but may overlook details. Sub-modeling can connect simulations across scales but is complex. Balancing trade-offs is crucial for battery performance. System-level analysis is vital for EV batteries. Computer simulations can expedite battery design. Atomic-scale simulations help select materials, while continuum-scale and machine learning optimize design. The growth of the EV market depends on factors like charging infrastructure, government regulations, and not just battery technology. Various factors like charging infrastructure and government regulations drive the EV market's growth. Extensive charging station coverage can ease consumer concerns, while proper government policies create an ideal environment for EV market growth. Collaboration among automakers, battery manufacturers, energy suppliers, and government bodies is expected to boost consumer demand and accelerate EV proliferation.

Prognostics and health management (PHM) involves overseeing the system's health, making decisions to extend its life. Prognostics warn of impending failures, aiding in addressing the issue [67]. Predictive health management estimates remaining useful life after detecting abnormalities [68]. Determining RUL and confidence are crucial in prognostic failure research [69]. Factors like storage voltage, discharge rate, etc., are considered in battery degradation monitoring [72]. LIB deterioration is complex and not suitable for real-time monitoring [73]. Capacity degradation models are used, but LIB failure happens when capacity drops [74]. Techniques like physical, data-driven, and hybrid are used for accurate BMS implementation [75].

2. Battery thermal problems

2.1. LIBs concern with extremely low/extreme conditions

Low-temperatures can significantly impact the performance and behavior of LIBs such as; reduced capacity (chemical reaction slow down), increased internal resistance (hinder the flow of electrons), voltage depression (voltage drop under load), slower charging (reduced chemical activity), and potential for damage (electrolyte freeze) [81]. On the other hand, high temperatures have several adverse effects on LIBs, potentially leading to reduced performance, shortened lifespan, and even safety hazards [82].

2.1.1. Low-temperature effects and promising solutions

At lower temperatures, battery reactions slow down, reducing capacity. Cold affects battery performance with significant reductions in runtime. Meyer et al. [83] explored the consequences of sub-zero temperatures on LIBs in Canada. Cold performance findings show reduced EV range at -7 °C compared to 20 °C. Extreme cold with maximum heating decreases EV range by 55 % to 60 % at -18 °C to -20 °C. Li et al. [84] perceived a pouch cell discharge capacity retained only 20 % at -40 °C . Jaguemont et al. [85] stated a LIB's discharge rate should be reduced at -25 °C to preserve capacity. Sub-zero temperatures can cause capacity reduction due to electrode polarization [86]. Fig. 8 shows graphic of the problems encountered by LIBs when operated under low-temperature conditions [87], the fundamental components affecting LIBs are reduction in Li+ diffusion constant in anode or cathode, increase in charge transfer process and Li+ diffusion constant, decrease in conductivity/viscosity of electrolyte. Carbon-based anode like graphite is seen as a bottleneck for low-temperature LIB application. Zhang et al. [88] examined factors impacting LIB performance: reduced ionic conductivity and wetting characteristics of liquid electrolytes, increased intrinsic grain-boundary resistance and slow Li+ diffusion rate in electrodes, presence of Li plating.

Researchers focus on optimizing the TMS for better battery temperature. Efforts are made to enhance materials and cell level by refining anode, cathode, and electrolyte materials [89]. This includes improving electrode porosity, compaction density, and thickness to enhance battery performance [90]. The cathode plays a crucial role in LIBs and influences EC performance [82]. Certain cathode materials such as $LiFePO_4$, Li3V2$(PO_4)_3$, NMC, and $LiMn_2O_4$ are suggested for enhancing LIB efficiency at low temperatures. Solutions like surface coating, doping, and particle size reduction can enhance battery capacity [91–94].

Surface coating is used to enhance cathode materials' low-heat ability by improving conductivity and structure stability [91]. Carbon coating is a well-known method for improving LiFePO4 EC performance by aiding electrolyte infiltration and inhibiting Fe2+ oxidation. A uniform carbon coating establishes a conductive network and enhances surface conductivity. Wrapping LiFePO4 spheres with carbon cages improves electron conductivity and capacity in low-temperature electrolytes [95,96]. Using graphene nanofibers forms a LiFePO4/C structure with enhanced capacities at low temperatures. Coating LiFePO4/C with fructose and calcium lignosulfonate shows notable capacity retention at low temperatures [97]. A 3D carbon-nanotube-decorated

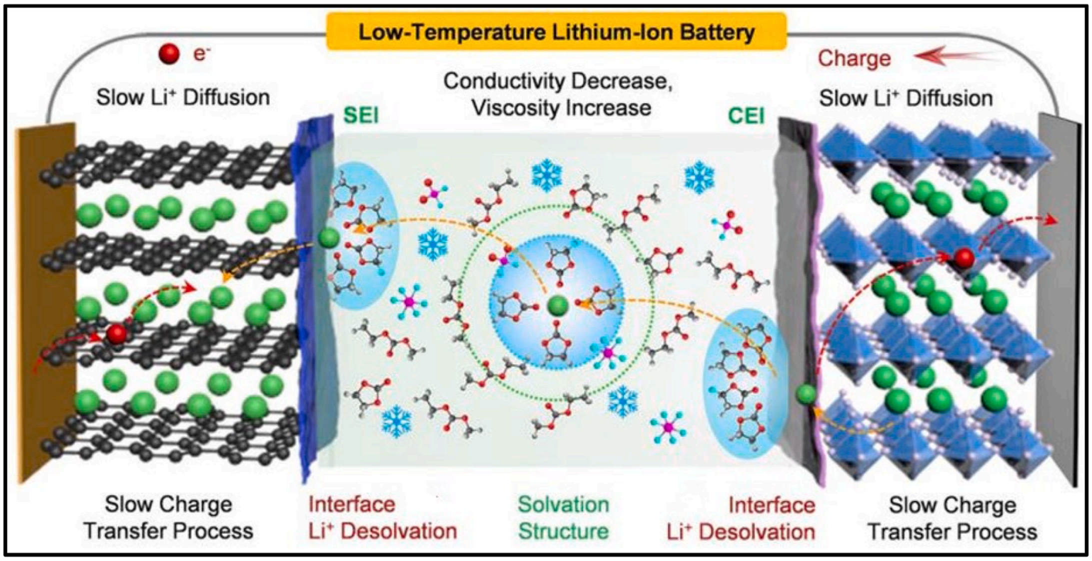

Fig. 8. Graphic of the problems encountered by LIBs when operated under low-temperature conditions [87].

nano-LiFePO4@C/CNTs composite design enhances low-temperature properties [98].

The amorphous carbon coating on LiFePO4 nanoparticles boosts Li+ diffusion capacity and stabilizes the interface, as shown by morphological studies [99,100]. Excessive carbon coating can lead to Fe2P formation and reduced tap density of LiFePO4, but alternative conductive polymers like polyaniline and polypyridine are being explored to enhance LiFePO4 conductivity [101,102]. Cai and team [103] showed how coating LiFePO4/C with Ti3SiC2 improved low-heat performance. Ti3SiC2 structure helped create conduction mode, reducing electron transfer rate [104,105]. This conflicted with Li+ diffusion rate, worsening low-temperature capacity [106]. TSC-4 maintained 97.0 % capacity retention at −10 °C and 1C after 100 cycles. Li3V2(PO4)3 has thermal instability, low ion immobility, and low irreversible capacity. Li3V2(PO4)3/C outperforms LiFePO4/C at low-heat [107]. Coating strategies are used to enhance Li3V2(PO4)3 low-heat capacity. CeO2 (2 %) in Li3V2(PO4)3/C reduces charge transfer resistance and increases capacity at low temperatures [108].

The NMC material merges positive traits of LiNiO2, LiCoO2, and LiMnO2 ternary layered materials. It displays exceptional flexibility, good stability, and low toxicity. Li(Ni0.6Mn0.2Co0.2)O_2 has the highest Li+ diffusion factor and no temperature dependence, achieving a capacity of 55 mAh/g at 0 °C, 5C. Increasing Ni content in NMC increases ions radius, optimizing Li slab space and enhancing low-temperature capacity. Ni, Co, and Mn in NMC have distinct impacts, each with strengths and weaknesses. Mn 4 plus stabilizes the structure, while Mn 3 plus is oxidized during synthesis, allowing for stable Ni 2 plus inclusion. However, Mn migration affects crystal structure and reduces capacity, which can be prevented at a cost. Ni, located between Mn and Co, improves capacity and structure stability [109,110].

Reducing particle size improves LiFePO4 performance by shortening diffusion paths, enhancing Li insertion/extraction, and boosting electron transfer speed [111]. Small particles with high surface area enhance contact with electrolyte for rapid Li+ diffusion [112]. The importance of particle size in EC performance was highlighted by Geng et al., [113] focusing on FePO4·2H2O size influence on LiFePO4 during carbon thermal reduction. Utilizing small FePO4·2H2O particles resulted in high purity LiFePO4 materials with enhanced rate capacity and cycling stability [114]. In the development of NMC, Ni, Co, and Mn show synergistic effects with unique advantages and disadvantages. The Mn3+/4+ orbital level is higher than Ni2+/3+, allowing stable integration of Ni2+ by oxidizing Mn3+ to Mn4+ without involvement in charge-discharge processes [115]. Mn4+ functions as a stabilizer to maintain structure, but its lower stability energy allows it to move to the Li plane, causing structural changes and decreased capacity [116]. Co, with higher stability energy, prevents this migration and maintains structure, yet it is costly and has environmental impacts. Ni has properties between Mn and Co, increasing material capacity and stabilizing structure. High nickel content in NMC enhances low-temperature capacity [117].

Graphite is widely used in LIBs due to its similarity to Li metal. However, at low temperatures, the graphite anode can degrade battery performance [118]. Challenges include reduced conductivity and thick SEI layer hindering Li+ diffusion. Maintaining optimal conductivities is crucial for efficient Li intercalation [119,120]. Achieving a stable SEI layer is essential for smooth Li+ diffusion. Challenges arise in maintaining SEI stability at low temperatures, leading to safety concerns [121]. Structural modifications can enhance SEI stability but may limit Li+ diffusion. Different graphite types show varying low-temperature characteristics [122]. Synthetic graphite demonstrates better performance at low temperatures compared to natural graphite [123,124].

Various strategies aim to enhance low-temperature properties of anodes by addressing key limitations. Capacity retention ratios and stability mechanisms are studied for diverse materials at different temperatures [125]. Methods involve modifying anode structure and composition for improved performance. Titanium oxides show better potential and stability compared to graphite anodes, preventing formation of metallic Li at low temperatures. Surface properties of these materials differ from low-potential anode materials. LTO and TiO2 face challenges in electrical and Li-ionic conductivity, especially in low temperatures. Proposed solution is a binder-free electrode with LTO composite, carbon nanotubes, and Ag nanocrystals for enhanced conductivity [126]. Fig. 9 shows key features of anode materials exhibiting enhanced low-temperature properties and the associated methodologies, retention ratios of capacity for diverse materials under varying temperatures, and elucidation of the enhanced EC stability mechanism for the SnO_2 anode at low-temperatures [127].

To improve cathode effectiveness at low temperatures, a technique uses various nanomaterials [128,129]. These batteries presented superb performance in diverse temperature settings, even as low as −40 °C [123]. A porous 2D structure increased contact area between electrode materials and electrolytes, providing more insertion sites for Li, thus enhancing overall performance. Changes in cathode surface chemistry led to a strong SEI layer with increased IC, achieving this improvement [130].

Ti_3C_2 MXene promotes fast Li+ and electron transfer, buffers Si

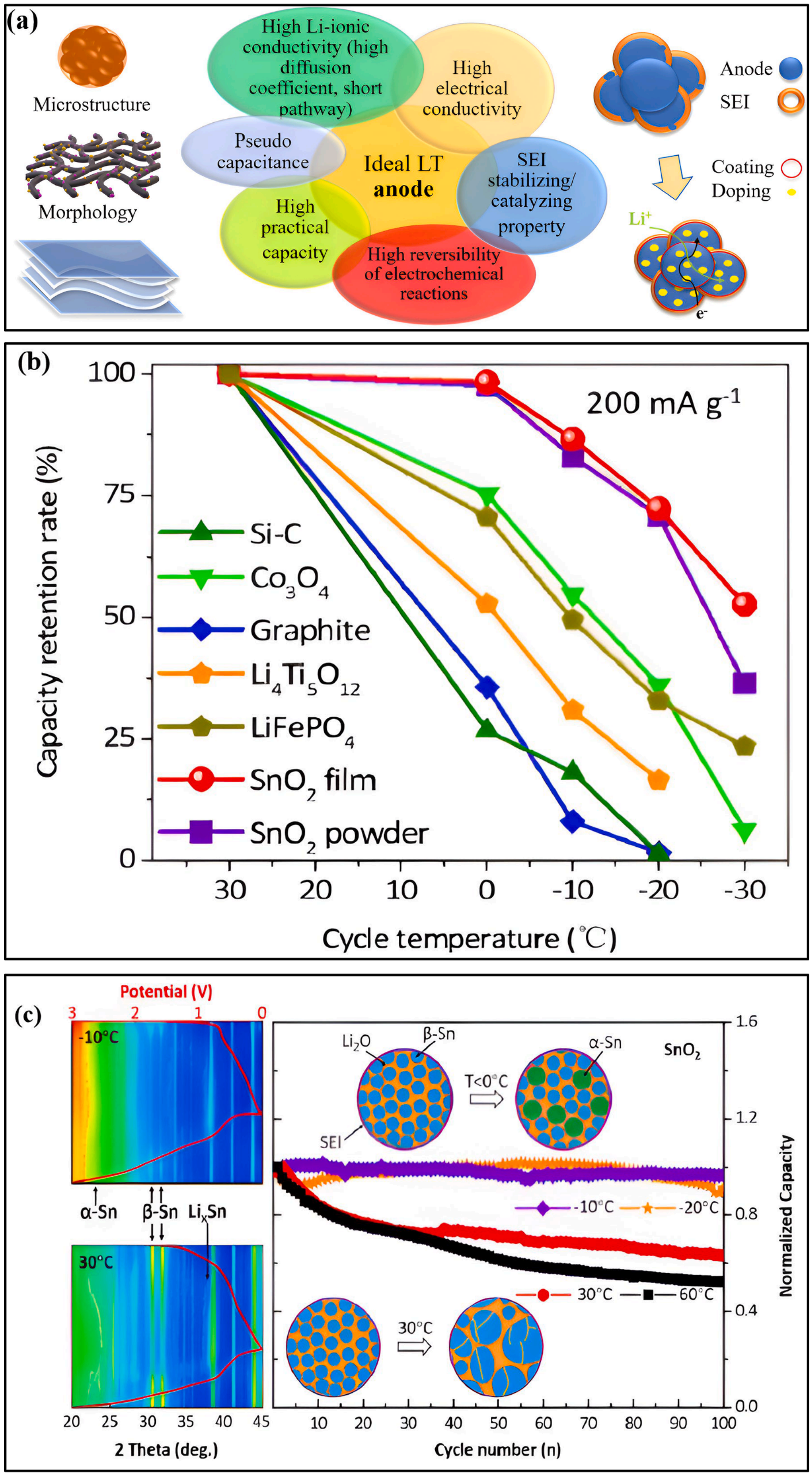

Fig. 9. (a) Key features of anode materials exhibiting enhanced low-temperature properties and the associated methodologies. (b) Retention ratios of capacity for diverse materials under varying temperatures, and (c) Elucidation of the enhanced EC stability mechanism for the SnO_2 anode at low-temperatures [127].

expansion, and enhances energy storage by improving pseudo-capacitive behavior. Surface redox sites are crucial for these enhancements. Specific surface chemistry changes in the cathode reduce resistance, improve Li+ intercalation, and create a stable SEI layer with better ionic conductivity [131]. CeB6 nanowires endure 6000 cycles at 1000 mA/g, maintaining stable performance at around 168 mA h/g due to high metal-like conductivity. Enhanced Li+ storage is attributed to surface capacitive behavior after the second cycle. Innovative methods by Yu et al. enhance VS4 anode conductivity through a 3D microstructure, achieving excellent EC performance at low temperatures with a capacity of 259.6 mAh/g at −20 °C [132]. Coating and doping improve electron and ion conductivity, influence SEI layer formation, and decrease C/D resistance [133,134]. Metal coatings on carbon anodes like Sn promote anion desolation and bulk electrode conductivity. Nb5+ doping in TiO2-coated LTO enhances conductivity and Li-ion diffusion [135]. Co-doped Zn2SnO4–graphene–carbon nanocomposite anode encounters difficulties at low temperatures [136]. Incorporating Co into Fe3C carbon nanofibers enhances electrical conductivity and reduces charge transfer resistance [137]. Adding Fe and Ag to carbon nanofibers improves electron conduction and charge transfer efficiency [138,139].

2.1.2. High temperature and promising solutions

The impacts at high temperatures are more complex than at lower temperatures. Heat is internally generated in LIBs, understanding this is important for reducing adverse effects at high temperatures in LIBs [140,141]. Fig. 10 shows graphic of categories of the HG within LIBs.

The importance of reliability and safety concerns related to excessive heat generation in LIBs acknowledged as a crucial technical obstacle [142]. These concerns might result in a significant decline in battery performance or possibly activate a thermal runaway, impeding the widespread adoption of Li-ion battery technologies [143]. Thinner electrodes rely more on reversible heat, while smaller active material particles enhance its effect due to lower reaction heat [144]. The integration of high energy batteries with organic electrolytes is a fire hazard due to the flammability of carbonate-based electrolytes. Abnormal abuse conditions can trigger TR, leading to destructive consequences. As battery size increases, the risk of fire incidents rises due to decreased heat dissipation area. Understanding reversible entropy change during battery operation is crucial. Entropy change values for single electrode reactions were consistently positive across different SOCs [145].

Understanding heat generation (HG) in different cell components of LIBs is essential for optimizing battery design [146]. Nazari and Farhad studied how HG varies with nominal capacities and chemistries in . They found that nominal capacity significantly impacts HG, with different ratios of reversible to total heat in various LIB chemistries. Calorimetric measurements provide insights into changes in battery conductivity and enthalpy of mixing, highlighting TiNb2O7 as a promising anode material for fast-charging batteries [147]. The need for fast progress in developing LIBs for high-temperature use arises from the demand for efficient energy storage systems. LiFePO4 shows better performance at high temperatures, with increased rate capability and capacity [148]. The use of LiBOB in LiTFSI-based electrolytes has been effective in reducing corrosion issues in aluminum current collectors at hot temperatures. LiFePO4 cells with LiTFSI–LiBOB-based electrolytes exhibit improved stability at 60 °C and similar performance at room temperature compared to cells with LiPF6-based electrolytes [149]. Researchers examined the use of LiFePO4 cathode at temperatures from 60 °C to 115 °C, showing improved high-rate performance up to 100 °C but increased polarization and impedance signals beyond that [150]. LiBOB is gaining attention in LIB salt research for its excellent thermal stability above 290 °C [151]. Although LiBOB has lower conductivity than LiPF6 in identical solvents, it can be beneficial at hot temperatures by improving both solubility and conductivity [152,153]. LiBOB is effective in cells operating between 60–115 °C [154,155].

2.2. Aging effect on battery performance

LIBs lifespan reduction due to factors like current rates, C/D cycle quantity and depth, storage conditions, and temperature exposure. Optimal operating temp for LIBs is 15° - 35 °C, but EVs can function between −20 °C to +60 °C [156]. Aging process in calendar mode (battery inactive) and cycling mode (charging/discharging cycles). LIB in calendar mode faces environmental conditions without temp regulation, while cycling aging involves BTMS regulating temp range [157]. Calendar mode leads to irreversible capacity loss during storage, affected by temperature and SOC. Cycling mode results in irreversible capacity loss during charging and discharging, influenced by factors like C-rate and ΔSOC [158]. Fig. 11 shows major aging factors of LIBs.

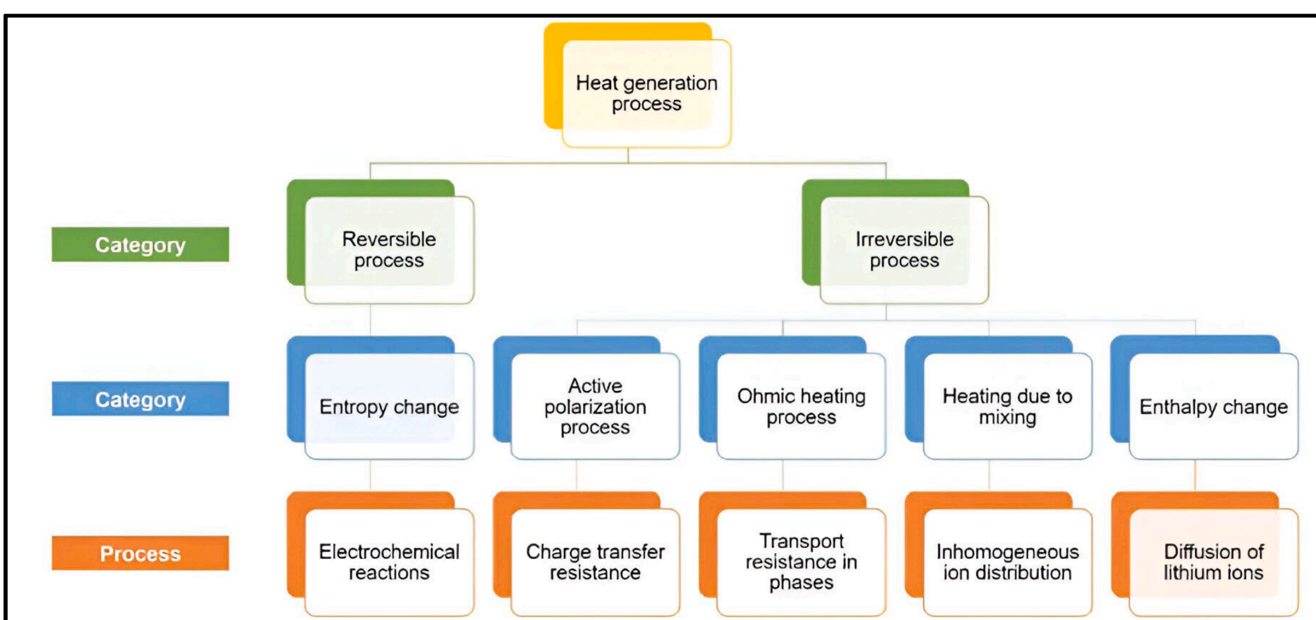

Fig. 10. Graphic of categories of the HG within LIBs.

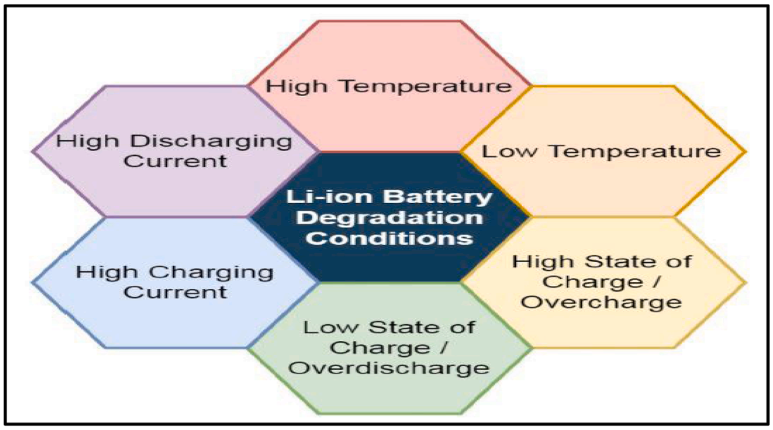

Fig. 11. Major Aging factors of LIBs.

2.2.1. *Key factors responsible for aging of LIBs*

i. **Effect of State of Charge**

The aging of LIB is affected by overcharging, over-discharging, and high DOD. Overcharging can induce TR by infusing outdoor energy [159]. Over-discharge causes irreversible capacity loss and stability changes, reducing resilience [160]. High SOC and high temperature together expedite degradation. Capacity faded in LIBs during cycling is similar to material fatigue. Minimizing SOC alterations during cycling increases battery lifetime. Maintaining an acceptable range for LIBs is crucial [161]. Overcharging and high SOC can lead to productivity and enactment degradation. Investigation on Lix(Ni0.3Co0.3Mn0.2)O2 LIB showed susceptibility to TR [162]. Restricting metal Li deposition and managing heat are vital for thermal safety during overcharge cycling [163]. Extending LIB lifetime can be achieved by reducing target SOC or rest phases at high SOC [164]. Optimal battery charging practices involve charging before departure to maximize efficiency [165]. Adjusting charging timing and frequency can enhance battery lifetime, known as smart charging [166,167].

ii. **Effect of Temperature**

Numerous augmented aging tests confirm environment temperature as key factor in LIB capacity degradation [168]. Different aging mechanisms exist at high and low temperatures. Research studies explain how temperature affects LIBs during storage and operation [169]. Extreme temperatures can speed up degradation processes, impacting battery health. Results show more severe degradation at low discharge rates [170]. Temperature greatly influences LIB behavior during operation, affecting internal resistance and electrode materials. Understanding this relationship is crucial for optimizing battery performance. Effective TMSs aim to regulate temperature for better battery longevity. Recommendations help users and manufacturers manage LIBsin varying temperatures [171].

The importance of charging LIBs within a specific temperature range [172], LIBs should be charged between 15 °C and 50 °C for optimal performance [173]. High temperatures increase internal resistance in batteries. Temperature greatly impacts the efficiency of LIBs. high temperatures accelerate battery aging in HEVs [174]. Temperature management is crucial for battery longevity in hybrid vehicles. the ideal operating temperature for LIBs in EVs is 15–35 °C [175]. Maintaining this range minimizes degradation and allows for cost-effective batteries. The economic benefits of keeping LIBs within a specific temperature range are highlighted. Hatzell et al. [176] conducted a study on the impact of temperature on battery health, emphasizing the effects of extreme temperatures on battery performance. Below −30 °C, cell impedance significantly increased, hindering charge and discharge efficiency. Temperatures above 60 °C led to severe capacity loss, with temperatures above 85 °C causing SEI layer decomposition. Degradation of the SEI layer can result in rapid deterioration and thermal runaway (TR), a dangerous condition in batteries. The research highlights the importance of temperature control in maintaining battery health, emphasizing the critical thresholds for detrimental effects. Managing temperatures within optimal ranges is essential to prevent impedance increase, capacity loss, and severe degradation or TR in LIBs used in EVs.

iii. **Effect of Charge/Discharge Rate**

The focus of research in the battery industry is on understanding the performance degradation mechanism of LIBs at high charging rates. Cell degradation is expedited by uneven distribution of current, temperature, and material stress due to increased charging rates [177]. The limiting factors involve the velocity of Li-ion intercalation and diffusion. High current rates can lead to various aging effects like metallic Li deposition and SEI growth [178]. Research conducted by Ning et al. revealed structural harm on graphite anode as C-rates rose, impacting capacity and resistance. High-rate discharge causes incomplete Li-ion transfer, leading to capacity fade and Li dendrite formation. Elevated current rates increase internal temperatures, amplifying active material loss and accelerating aging. Different degradation mechanisms were observed by Mussa et al. [179] based on charging rates, such as Li plating at 3 C and graphite exfoliation and gas evolution at 4 C. Wang et al. [180] found a correlation between temperature and C-rate, with varying impacts at different temperatures. Capacity retention trajectory differs notably at different C-rates and temperatures, indicating accelerated Li plating at higher C-rates. Studies show the differing impacts of individual factors on battery degradation. Factors like battery chemistry, test conditions, and other degradation factors affect degradation severity. Cycling temperature, SOC, C/D rate, and storage temperature collectively influence battery degradation rate. Knowledge of these interactions is crucial for improving battery performance and lifespan.

3. Thermal modeling a LIBs

3.1. *General organization*

Battery models are essential for understanding LIBs features; they are crucial for developing BMS algorithms. These models explain factors like load current, temperature, and voltage affecting battery efficiency.

Vehicle battery systems need modeling for monitoring, diagnosis, and control via a BMS, which is challenging due to diverse working environments. Three types of models - EC, empirical, and semi-empirical - accurately replicate experimental data like charging time and voltage despite differences in application and detail level. In every system, internal heat is mainly moved through thermal conduction. This is especially valid if convective heat transfer is limited due to restricted movement of electrolyte and gas. The assumption holds as long as convective heat transfer remains constrained. The alteration in thermal energy stored in a system's control volume over time equals the discrepancy between HG and the total heat diffusion out of the system. This association is mathematically described by the following equation [181,182]:

$$\left.\begin{array}{l}\dfrac{\partial(\rho c_p T)}{\partial t} + \nabla(k\nabla T) = R \\ R = R_{abuse-chem} + R_{joul} + R_{combustion} + \ldots\ldots\end{array}\right\} \tag{1}$$

where the symbol ρ (g/cm^3) is used to represent density in the context of this discussion. The symbol c_p (J/gK) is employed to denote heat capacity. The symbol T (K) is used to signify temperature. The symbol t (s) stands for time. The symbol k (W/cmK) is employed to denote Thermal Conductivity (TC). The symbol R (W/cm^3) is utilized to represent the terms for heat source/sink.

The thermal analysis of a battery in three dimensions encompasses the volumetric generation of heat that arises from the reactions taking place within the components of a LIB across different temperatures. The integration of this HG into the analysis is achieved by expressing it and incorporating it through the utilization of the subsequent equation:

$$R_{abuse-chem} = R_e + R_{pe} + R_{ne} + R_{sei} + R_{nb} \tag{2}$$

where the heat from the SEI decomposition reaction is denoted by R_{sei}, whereas the reaction between the negative active material and electrolyte is represented by R_{ne}. The reaction between the positive-active material and electrolyte is signified by R_{pe}. The decomposition of the electrolyte is denoted by R_e, while the reaction between the negative active material and binder is represented by R_{nb}.

In the evaluation of the transfer of heat between the given system and its surrounding environment, calculations are performed by employing thermal boundary situations that are assigned to the boundaries of the computational domain. These combined thermal boundary conditions have the objective of integrating both radiation and convection HT contributions that are exerted on the surface of each cell. The calculation of the convective heat flux that is directed outward towards the ambient environment is conducted by employing the equation provided below.

$$q''_{conv} = h\left(T_{surf} - T_{amb}\right) \tag{3}$$

where, the letter h represents the convection HT quantity.

In the process of conducting simulations that aim to imitate oven tests, the ensuing equation is employed for the purpose of calculating the radiative heat flux as it emanates from the surface of the cell and propagates towards the surrounding environment.

$$q''_{radi} = \varepsilon\sigma\left(T^4_{surf} - T^4_{amb}\right) \tag{4}$$

where ε is utilized to denote the emissivity of the cell surface and σ is employed to represent the constant Stefan-Boltzmann. It is assumed that the oven chamber is a thermally stable enclosure in which the irradiation is equivalent to the emission from a blackbody. Within this framework, the cell surfaces are regarded as gray diffuse surfaces.

The main contribution of heat generation are the reaction heat (q_{re}) caused by enthalpy change of the reaction, Ohmic heat (q_{ohm}) caused by internal contact resistances, and polarization heat (q_{act}) caused by the difference between the equilibrium potential and the terminal voltage [57–59]. The reaction heat is defined as reversible heat (q_{rev}) due to that the heat effect can be reversed or recuperated during charging and discharging cycles. Correspondingly, the Ohmic heat and polarization heat in batteries are termed irreversible heat (q_{irr}) due to their nature of permanently converting electrical energy into thermal energy without the possibility of reversal. Therefore, the total heat generation inside of the battery q, can be also expressed as [183]

$$q = q_{rev} + q_{irr} = q_{re} + q_{ohm} + q_{act} \tag{5}$$

where

$$q_{re} = J_{Li}T\frac{\partial U}{\partial T} \tag{6}$$

$$\begin{aligned}q_{ohm} = {} & \sigma^{eff}(\nabla\phi_s)^2 + \kappa^{eff}(\nabla\phi_e)^2 \\ & + \frac{2RT\kappa^{eff}}{F}\left(t^0_+ - 1\right)\left(1 + \frac{\partial \ln f}{\partial \ln c_e}\right)\cdot\nabla(\ln c_e)\cdot\nabla\phi_e\end{aligned} \tag{7}$$

$$q_{act} = J_{Li}(\phi_s - \phi_e - U) \tag{8}$$

In electrochemical models, some parameters are temperature-dependent, for example, open circuit potential (OCP), ionic conductivity (κ), Li-ion diffusion coefficient in solid phase (D_s) and electrolyte phase (D_e) [184]. Therefore, solving an electrochemical-thermal coupled model requires that at the end of each time step, the temperature calculated from the thermal model is fed back into the electrochemical model. Then, using these re-estimated temperature-dependent parameters, the coupled model is computed for the next time step [185]. Fig. 12 describes an example of electrochemical-thermal model.

3.2. Thermal abuse models

Thermal abuse models predict system behavior under extreme temperatures by considering chemical, thermal, and physical factors. They improve safety evaluations and design through complex equations addressing electrolyte decomposition and short-circuiting. These models enhance the safety and reliability of energy storage systems by mitigating risks. Four reactions occur during jelly-roll decomposition: electrolyte, positive-electrolyte, negative-electrolyte, and SEI. Reaction rates are determined by both temperature and material characteristics in Arrhenius form.

3.3. Electrochemical models

EC models serve as complex structures employed for comprehending, simulating, and forecasting the conduct of EC systems, notably batteries and fuel cells. These models explore the fundamental chemical and physical mechanisms transpiring within these systems, encompassing phenomena such as charge transfer, ion diffusion, electrode reactions, and mass transport [187].

Typically, they encompass interconnected systems of equations that are deduced from fundamental EC principles, which encompass [181, 182]:

3.3.1. Reaction of electrolyte decomposition

Electrolyte decomposition reaction occurs in batteries or EC cells due to chemical breakdown of electrolyte. Factors like high voltages, extreme temperatures, or repeated cycling can trigger this reaction. The decomposition leads to gas formation, solid deposits (e.g. SEI), or release of volatile compounds. These byproducts can disrupt battery function causing performance decline, capacity loss, and safety risks like gas buildup or overheating.

The electrolyte can experience exothermic decomposition when subjected to elevated temperatures, specifically temperatures exceeding 200 °C. This phenomenon is elucidated through the following equations:

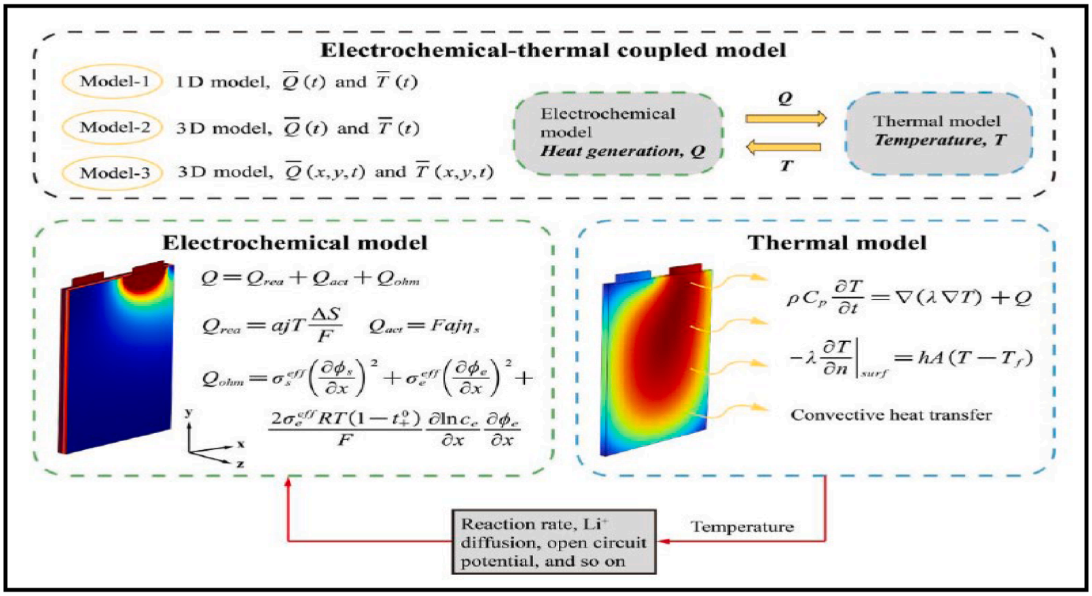

Fig. 12. Description of the electrochemical-thermal coupled model [186].

$$\left.\begin{aligned} R_e(T, c_e) &= A_e H_e W_e \exp\left(-\frac{E_e}{RT}\right)c_e \\ \frac{dc_e}{dt} &= -A_e \exp\left(-\frac{E_e}{RT}\right)c_e \end{aligned}\right\} \tag{9}$$

where c_e denotes the dimensionless concentration of electrolyte, and R_e (1/s), A_e (1/s), and E_e (J/mol) represent the reaction limitations. The heat release, denoted as H_e (J/g), is calculated as the number of joules released per gram of electrolyte, while W_e (g/m^3) refers to the volume-specific content of electrolyte.

3.3.2. Reaction of a positive solvent

The positive solvent reaction pertains to the chemical interactions that occur between the materials constituting the positive electrode (cathode) and the solvent molecules present within the electrolyte in EC devices such as batteries. In several battery chemistries, especially LIBs, the solvent, which acts as the medium for ion transportation, has the potential to affect and participate in chemical reactions with the materials comprising the positive electrode during the processes of charging and discharging. These reactions taking place at the interface between the electrode and the electrolyte can initiate various phenomena. They may involve the creation of surface films or layers, the generation of novel chemical compounds, or modifications in the composition and structure of the electrode materials.

In the oxidized condition, the affirmative substance undergoes direct interaction with the electrolyte, or the affirmative active substance has the capability to undergo exothermic decomposition and release oxygen, which can subsequently react exothermically with the electrolyte. In either scenario, the compound reduction of the affirmative active substance with the electrolyte is governed by significantly exothermic equations as indicated below:

$$\left.\begin{aligned} R_{pe}(T, \alpha, c_{pe}) &= \alpha(1-\alpha)A_{pe} H_{pe} W_{pe} \exp\left(-\frac{E_{pe}}{RT}\right) \\ \frac{d\alpha}{dt} &= \alpha(1-\alpha)A_{pe} \exp\left(-\frac{E_{pe}}{RT}\right) \end{aligned}\right\} \tag{10}$$

where the symbol α is used to denote the degree of conversion. R_{pe} (1/s), A_{pe} (1/s), and E_{pe} (J/mol) are the designations for the reaction parameters. The calculation for the specific heat release, denoted as H_{pe} (J/g), involves determining the energy in joules released per gram of positive-active content. Meanwhile, the quantity W_{pe} (g/m^3) represents the volume-specific positive-active content.

3.3.3. Reaction of a negative solvent

The negative solvent reaction concept typically pertains to the interactions or chemical processes that occur between the negative electrode (anode) materials and the electrolyte solvent in EC devices, particularly batteries. In multiple battery systems, like LIBs, the solvent molecules in the electrolyte can potentially interact with the constituent materials of the negative electrode during charge and discharge cycles. These connections at the intersection amidst the undesirable electrode and the electrolyte solvent might result in an assortment of occurrences. These may encompass the formation of surface films or layers, chemical modifications in the electrode materials, or the production of novel compounds.

At temperatures exceeding 120 °C, a chemical reaction characterized by the release of heat can take place between Li that is intercalated and the electrolyte. This reaction can be described as follows:

$$\left.\begin{aligned} R_{ne}(T, c_{ne}, z) &= A_{ne} H_{ne} W_{ne} \exp\left(-\frac{z}{z_0}\right)\exp\left(-\frac{E_{ne}}{RT}\right)c_{ne} \\ \frac{dc_{ne}}{dt} &= -A_{ne} \exp\left(-\frac{z}{z_0}\right)\exp\left(-\frac{E_{ne}}{RT}\right)c_{ne} \\ \frac{dz}{dt} &= A_{ne} \exp\left(-\frac{z}{z_0}\right)\exp\left(-\frac{E_{ne}}{RT}\right)c_{ne} \end{aligned}\right\} \tag{11}$$

where the dimensionless quantity of Li intercalated within the carbon is denoted by c_{ne}. A dimensionless measure of the SEI layer thickness, reflecting the amount of Li in the SEI, is represented by z. The reaction parameters are characterized by R_{ne} (1/s), A_{ne} (1/s), and E_{ne} (J/mol). The specific heat release, H_{ne} (J/g), is computed as joules per gram of carbon. The volume-specific carbon content is denoted by W_{ne} (g/m^3).

3.3.4. Decomposition reaction of the SEI

The decomposition reaction of the SEI pertains to the chemical process transpiring at the interface connecting the electrode and the electrolyte within batteries, especially LIBs. This reaction encompasses the creation and subsequent disintegration of a slim, passivating layer termed the SEI, which spontaneously forms on the electrode surface due to the decomposition of the electrolyte. The SEI serves as a protective coating, impeding further decomposition of the electrolyte and ensuring consistent battery performance. However, under specific circumstances such as exceedingly high voltages or temperatures, the SEI may deteriorate, resulting in its decomposition and the subsequent production of novel compounds.

The negative electrode is secure from direct response with the solvent by a layer called the SEI, which conducts ions. This layer, while being unstable, can go through a heat-releasing decomposition process that typically happens at temperatures between 90 and 120 °Celsius. The representation of this reaction can be stated by the equations provided below [188].

$$\left.\begin{aligned} R_{sei}(T, c_{sei}) &= A_{sei} H_{sei} W_{sei} \exp\left(-\frac{E_{sei}}{RT}\right) c_{sei} \\ \frac{dc_{sei}}{dt} &= -A_{sei} \exp\left(-\frac{E_{sei}}{RT}\right) c_{sei} \end{aligned}\right\} \tag{12}$$

where the dimensionless quantity of Li-containing meta-stable species in the SEI is represented by c_{sei}. The reaction parameters R_{sei} (1/s), A_{sei} (1/s), and E_{sei} (J/mol) are associated with the SEI. The heat release per unit mass, H_{sei} (J/g), is determined as the amount of energy released in joules per gram of carbon. The volume-specific carbon content is denoted by W_{sei} (g/m^3).

3.4. Empirical model

An empirical model refers to a mathematical depiction or formulation that is attained through the examination of observations, experiments, or empirical data, rather than being exclusively founded on theoretical principles or underlying physical laws. The primary objective of such a model is to encompass and elucidate the connections, patterns, or behaviors observed in data without explicitly considering the mechanisms that propel these connections. Empirical models are formulated via statistical analysis, curve fitting, or data-driven methodologies in order to prognosticate or simulate results grounded on observed data points. They may vary from uncomplicated equations deduced through data fitting to more intricate algorithms such as regression models, decision trees, or machine learning models.

3.5. Semi-empirical models

Semi-empirical models achieve a harmonious equilibrium between observed phenomena and conceptual comprehension. These models are formulated by amalgamating observed data with theoretical tenets or fundamental principles. Frequently, they amalgamate empirical constants, parameters, or associations within a structure that is founded upon established theoretical fundamentals. The characteristic that sets semi-empirical models apart is their capacity to amalgamate observed data with theoretical insights. Although they utilize empirical data to capture real-world behavior or patterns, they also integrate theoretical components to augment their precision or predictive abilities.

3.6. Electrical model

The devised electrical model represented a model of internal resistance, which aimed to simplify the battery system by including only an internal voltage source and resistance. The determination of the internal voltage source within this model was contingent upon a multitude of factors. These factors included the capacity of the battery, which was subject to variation due to changes in temperature, as well as the SOC and SOH. On the other hand, the resistance exhibited distinctive characteristics for the processes of charging and discharging. Both resistances were dependent on the battery's SOC and SOH. This recognition of differentiation acknowledged the fact that the resistance displayed distinct behaviors during the charging and discharging phases, which were subject to alteration based on the battery's charge level and health status.

In addition, the model adopted the incorporation of two essential health-related measurements: the Capacity SOH and the Resistance State of Health (SoHR). SoHC illustrated the battery's ability to retain capacity, thereby indicating the extent to which the battery maintained its initial capacity over a period of time. The model of internal resistance that was employed can be observed in Fig. 13.

Conversely, SoHR concerned the rise in internal resistance, thereby indicating the battery's impedance alterations as a result of usage and aging. By amalgamating these elements, the framework facilitated the disentanglement or dissociation of two pivotal deteriorative factors: Capacity Erosion (CE), which alludes to the decline in the combined capacity of the battery throughout its functioning lifespan, and Power Erosion (PE), which signifies the diminishing capability of the battery to generate power. This disjunction enabled a more comprehensive scrutiny and comprehension of the distinct deteriorative mechanisms that influence the battery's efficiency over time.

The determination and calculation of the terminal voltage can be achieved through the utilization of the subsequent mathematical formulation [189].

$$V_T(t) = V_{OC}(SoC) - R(SoH_R, SoC) \times I(t) \tag{13}$$

where $V_T(t)$ is an indicator of the terminal voltage at each specific point in time, $V_{OC}(SoC)$ refers to the open circuit voltage that corresponds to the SoC. R (SoH_R, SoC) represents the internal resistance value that is determined by both SoH_R and SoC. Lastly, I(t) denote the current value at each specific point in time. Fig. 14 shows an open circuit voltage curve graph.

The voltage that occurs when there is no circuit connected, commonly referred to as the open circuit voltage (VOC), is illustrated in Fig. 14 by utilizing the PCHIP interpolation method. The determination to utilize this interpolation method was predicated on its capacity to effectively sustain the monotonicity of the data. The Eq. (1) displays the PCHIP interpolation polynomial [190,191] that was employed in this study.

$$y(x) = \left\{\begin{matrix} h_{00}(t)y_k + h_{10}(t)(x_{k+1} - x_k)m_k + \\ h_{01}(t)y_{k+1} + h_{11}(t)(x_{k+1} - x_k)m_{k+1} \end{matrix}\right\}, \text{ for } k = 1, 2, ..., n \tag{14}$$

Where x signifies the distinct input value, $y(x)$ shows the estimated value, x_k and x_{k+1} refer to the values preceding and succeeding x, respectively. Similarly, y_k and y_{k+1} pertain to the values preceding and succeeding y(x), respectively. m_k and m_{k+1} represent the tangents assessed at points k and $k + 1$ respectively. Furthermore, $h_{ii}()$ is an abbreviation for the basic Hermite function, and t represents the point at which each $h_{ii}()$ is evaluated. The values of t and m_k were ascertained through the utilization of the subsequent equations.

$$\left. t = \frac{x - x_k}{x_{k+1} - x_k}, m_k = \frac{\Delta_{k-1} - \Delta_k}{2} \right\} \tag{15}$$

The slopes of the secant lines between successive points, represented by Δ_{k-1} and Δ_k can be expressed in the following equation.

$$\Delta_k = \frac{y_{k+1} - y_k}{x_{k+1} - x_k} \tag{16}$$

The fundamental Hermite functions, denoted as $h_{ii}()$, are established through the subsequent mathematical expressions:

$$\left.\begin{aligned} h_{00}(t) = B_0(t) + B_1(t), \quad h_{10}(t) = \frac{1}{3}B_1(t) \\ h_{01}(t) = B_2(t) + B_3(t), \quad h_{11}(t) = B_0(t) + B_1(t) \end{aligned}\right\} \tag{17}$$

The constituents of the Bernstein polynomials of order 3 are the elements B_i, which form the components responsible for constructing $h_{ii}()$. These elements can be represented by the equation that follows.

$$B_i(t) = \binom{3}{i} t^i (1 - t)^{3-i} \tag{18}$$

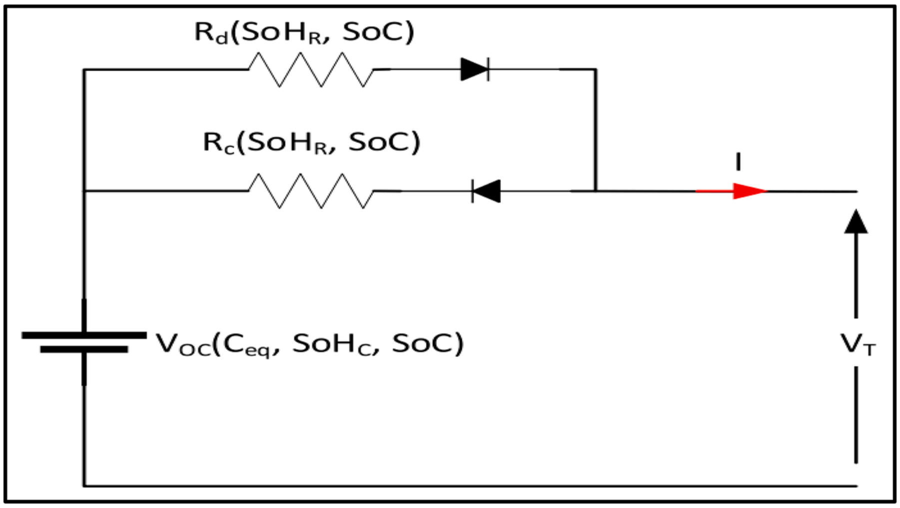

Fig. 13. Internal Resistance Model [189].

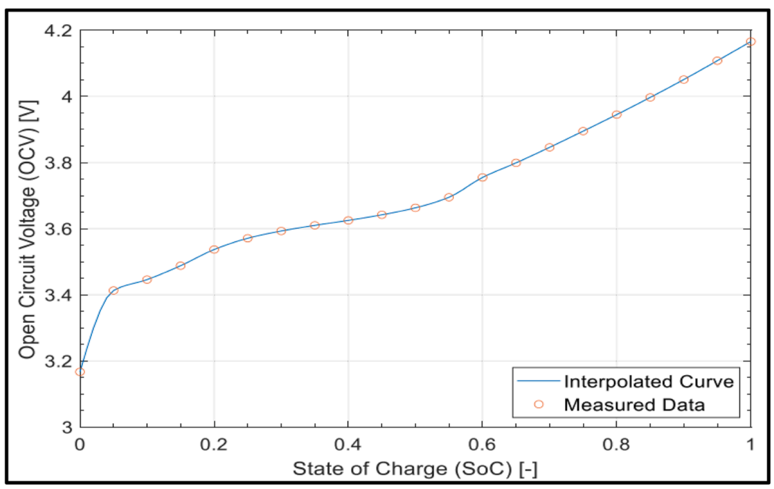

Fig. 14. Open circuit voltage curve graph.

The open circuit voltage curve was exclusively examined at 25 °C, and therefore, the analysis of the open circuit voltage was not conducted with respect to temperature.

4. Battery thermal problem mitigation

Battery BTMS are created to control battery temperature for better performance and longer lifespan. Various methods are proposed in literature. One method is adding an aerogel coating to the housing to regulate temperature and extend lifespan. Another method uses a water tank, filtering plate, and collection box to dissipate heat effectively. A different system uses PCM, cooling fan, and air outlet to minimize heat accumulation and reduce costs. Additionally, a BTMS with liquid cooling, mounting chambers, and ventilation channels is suggested for stable cooling and enhanced effectiveness. Advancements in BTMS technologies focus on improving EV efficiency and dependability. More advanced cooling strategies like PCM and direct liquid cooling are being explored. Direct liquid cooling shows promise for enhancing battery performance in various conditions, but further research is needed for widespread use in EVs. Effective TMSs are crucial for battery safety, energy optimization, and vehicle lifespan. Integrating air conditioning systems, BTMS, and motor TMSs is expected to boost energy efficiency. Challenges for existing TMSs include system integration, control algorithms, performance balance, and cost estimation. These BTMS advancements have the potential to enhance EV performance and lifespan, making them a more viable option in the transportation sector.

4.1. Immersion cooling

Immersion cooling technology for lithium battery packs is an advanced method of battery cooling, primarily used to enhance thermal management efficiency in electric vehicles and other high-energy-density battery systems. This technology involves immersing the entire battery pack or individual battery cells into non-conductive dielectric cooling fluid, such as hydrocarbon oils, silicone oils and fluorinated hydrocarbons, to effectively control the temperature of the batteries. Immersion cooling offers superior temperature uniformity for battery packs and cells compared to other cooling methods. This is due to the complete submersion of battery surfaces in fluid, which provides a uniform, high-capacity thermal path for heat dissipation. Direct contact with cell surfaces also minimizes thermal contact resistance seen in indirect cooling systems. This method simplifies system design and reduces complexity. Additionally, immersion cooling often prevents thermal runaway, as some dielectric fluids used are flame-retardant, thus improving the safety of the lithium-ion battery pack [192].

4.2. Air cooling

BTMS with air cooling studied in EVs and energy storage. Optimization methods suggested to improve cooling efficiency [193,194]. These studies provide insights for the design and optimization of air-cooled BTMS [195–197]. The performance of air-cooling systems in BTM is influenced by factors such as geometrical configurations like plenum angle and widths [198]. Factors like inlet and outlet positions, battery spacing, and air velocity also significantly affect the CP [199]. Metal fins can enhance heat dissipation and CP in air cooling systems. Air cooling combined with liquid cooling can further improve CP, especially under high discharge rates [200]. Optimization of factors is crucial for efficient cooling and temperature control in BTMS. Adjusting plenum angle, widths, inlet position, and baffle setting can improve air cooling system efficiency in BTM [201]. Combining active and passive TMS with PCM can enhance cooling efficiency and reduce energy consumption. Metal fin intensified PCM system coupled with air cooling improves heat dissipation and lowers maximum BT [202]. Introduction of HT fins into the module enhances CP but may increase energy consumption [203]. Utilization of PCMs and system design optimization effectively enhance air cooling system efficiency in BTM [204].

The battery's efficacy and lifespan are affected by its thermal control setup arrangement. Effective heat dissipation is crucial to prevent rapid aging [205]. Maintaining the battery at 22–30 °C enhances its condition [206]. Cooling techniques like air, liquid, and PCM cooling are used by BTMS [207]. Liquid cooling plates and heating films control temperature rise effectively [208]. Proper thermal management is vital for battery performance enhancement [209]. Optimization of air ducts and space ratio enhances BPs efficiency and temperature uniformity [210]. Improving TMS design can enhance battery effectiveness and lifespan. BTMSs may not be crucial for managing battery EC performance [211]. Techniques like multi-objective optimization boost BTMS cooling and heating performance [212]. Optimizing geometric parameters and nanoparticle volume controls thermal issues. Innovative cooling technologies like pulsating heat pipes are recommended. Combining air and liquid cooling reduces energy consumption at high discharge rates. Ultimately, TMS design optimization leads to improved efficiency and battery lifespan [201]. Fig. 15 shows outline of the air-cooling battery thermal management system.

4.3. Liquid cooling

BTMS using liquid cooling is proposed for maintaining optimal temperature in LIBs. Various liquid cooling plates with mesh structures are compared to improve TU and reduce heat concentration [214]. Despite the drawback of increased weight, liquid cooling outperforms PCM and air cooling [215]. A new BTMS combines water cooling with thermoelectric cooling and PCM to regulate BP temperature effectively [216]. A model combining CPCM with liquid cooling is proposed to reduce battery spacing and enhance TU during charging/discharging [217]. A liquid cooling BTMS with a silicone hose is suggested for optimizing CP and energy consumption by investigating different pump strategies [218].

Liquid CSs are a promising advancement in BTM for energy storage. They offer effective temperature control for safe battery operation. Research includes PCM and direct liquid cooling techniques. PCM cooling maintains BTs below 40 °C, while direct liquid cooling ensures desired battery performance [219]. Advanced strategies like liquid cooling plates with mesh structures enhance TU and reduce heat concentration [220]. These advancements improve efficiency, reliability, and capacity of BPs for energy storage technology [221,222].

Liquid CSs enhance battery performance by controlling flow rate and inlet temperature. CS with a coolant temperature of 15 °C and flow rate of 2 L/min shows superior cooling capabilities [223]. A novel BTMS with a silicone hose reduces BT by 10 °C, keeping battery temperature within the appropriate range [224]. Thermal performance of liquid-cooled battery modules is examined through simulations to evaluate optimal coolant for different velocities [225,226]. Liquid cooling enhances safety and dependability of battery systems. It maintains optimal temperatures, extends battery lifespan, and improves EV safety. Liquid cooling reduces maximum temperatures, ensuring batteries operate within the correct range. It also promotes thermal uniformity in battery packs for better safety and performance. Liquid cooling regulates battery pack temperatures, slowing aging and preserving battery condition. Different cooling mediums and velocities can be used for optimal thermal performance. Overall, liquid cooling is crucial for enhancing safety, dependability, and performance of battery systems in various applications. Fig. 16 shows battery liquid cooling system with different cooling channel arrangements.

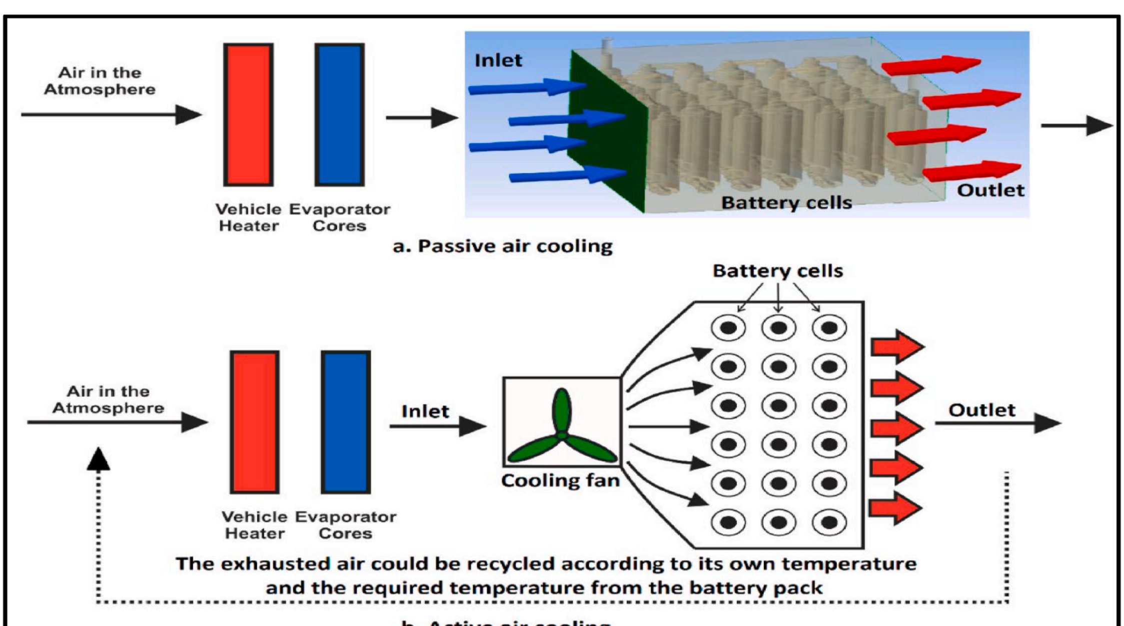

Fig. 15. Outline of the air-cooling battery thermal management system [213].

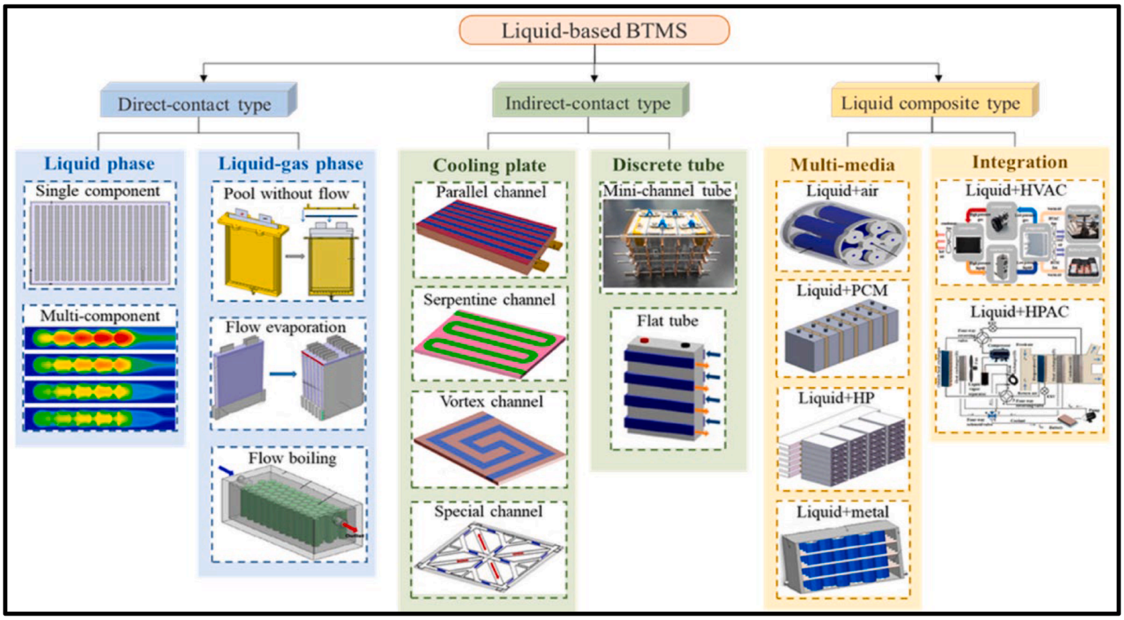

Fig. 16. Battery liquid cooling system with different cooling channel arrangements [227,228].

4.4. PCM cooling

PCM-based BTMS proposes a strategy to regulate LIBs temperature. PCM helps with heat absorption and keeping temperature safe without external devices. Research focuses on PCM in BTMS like hybrid systems and PCM with metal fins. Novel BTMS use water cooling, thermoelectric cooling, and PCM. A heat dissipation model integrates PCM with liquid cooling for better temperature control. PCM-based BTMS are popular for keeping temperature safe without extra power or complex devices.

The performance of PCM cooling in managing BT is affected by various key factors. Factors include PCM thickness, diameter and number of metal fins, air inlet velocity, airflow temperature, cooling mode, PCM melting point, size of PCM mandrel, TC anisotropy, cooling duct structure, and cold air stream pressure difference [229,230]. Metal fins in PCM system improve heat dissipation and reduce maximum BT. Higher air velocity helps recover latent heat from PCM but increases power consumption. Internal cooling is more effective than external cooling. PCM mandrel size and radial TC impact battery temperature distribution [231]. Achieving TU is aided by reducing battery size in the stratiform direction. Combining lively TMS and passive TMS with PCM in hybrid BTMS enhances cooling efficiency and reduces energy consumption. Regulating inlet flow rate and coolant temperature in liquid CS optimizes utilization of composite PCM latent heat and decreases energy consumption. TECs and PCM lower BP temperature compared to forced convection cooling, with system's coefficient of performance influenced by cooling modules number and inversely by thermoelectric coolers power [232]. The design and configuration of PCM-CSs affect BT regulation. One study showed a metal fin PCM system with air cooling had better CP. This system reduced maximum BT by 18.6 %. Internal cooling with PCM was found to perform better than external cooling. CP

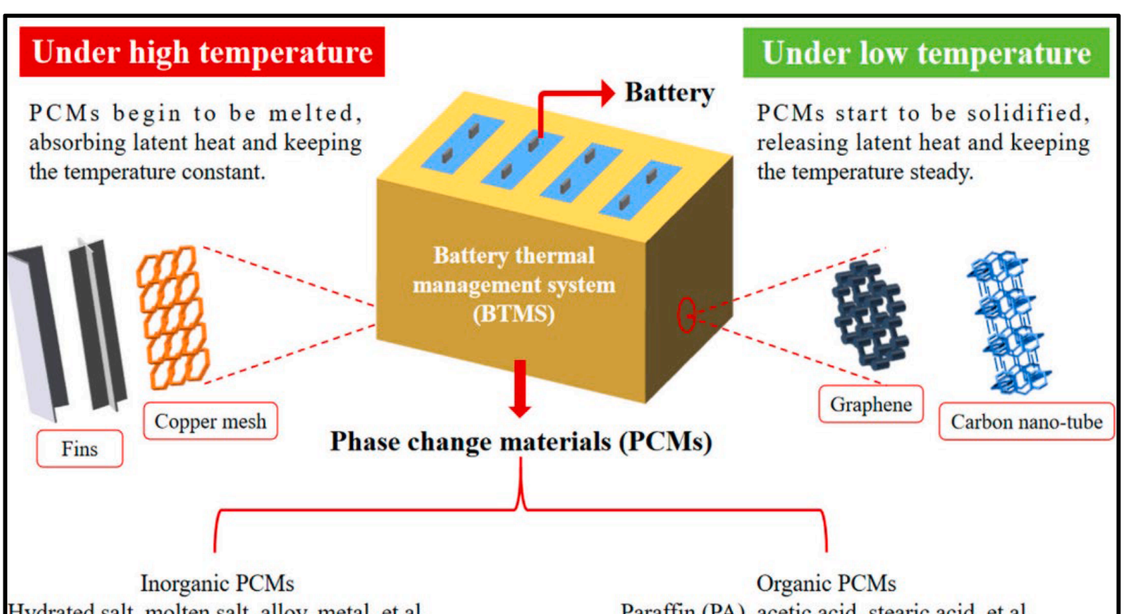

Fig. 17. Schematic representation of Phase change materials battery cooling system [233].

was affected by TC anisotropy and PCM mandrel size. A serpentine tube liquid cooling system with composite PCM effectively regulated BT. This system reduced energy consumption by using PCM latent heat. Design parameters like fin configuration and PCM properties are crucial for enhancing PCM-CS efficiency for BTM. Fig. 17 shows schematic representation of Phase change materials battery cooling system.

Although PCMs offer many benefits, they have inherent weaknesses that hinder their practical use in BTMs. Chief among these are poor thermal stability and flammability, which have thus become key areas of research. The thermal stability of PCMs poses significant challenges. During phase transformations, such as solid-liquid and liquid-gas changes, volume fluctuations and the movement of the dispersed phase in PCMs often lead to a decline in their mechanical and thermal properties. The flame retardancy of PCMs is a crucial thermal safety feature for effective battery thermal management. It can protect a battery system from thermal runaway (TR) spread due to internal short circuits or external pressure. Conversely, flammable PCMs can contribute to the spread of TR within a battery system. Therefore, given the occasional accidental fires and the rising energy density of commercial batteries, it is crucial to focus on the thermal hazard mitigation capabilities of PCM-based BTMs. Alleviating battery thermal runaway (TR) propagation is a major research focus. Current methods are generally categorized into two types: inserting thermal barriers between battery cells or enhancing heat dissipation, or both methods can be implemented simultaneously. However, there is still limited literature on this topic, and more research is needed [234]

4.5. Heat pipe cooling

Heat pipe- BTMS are extensively studied for maintaining EV battery

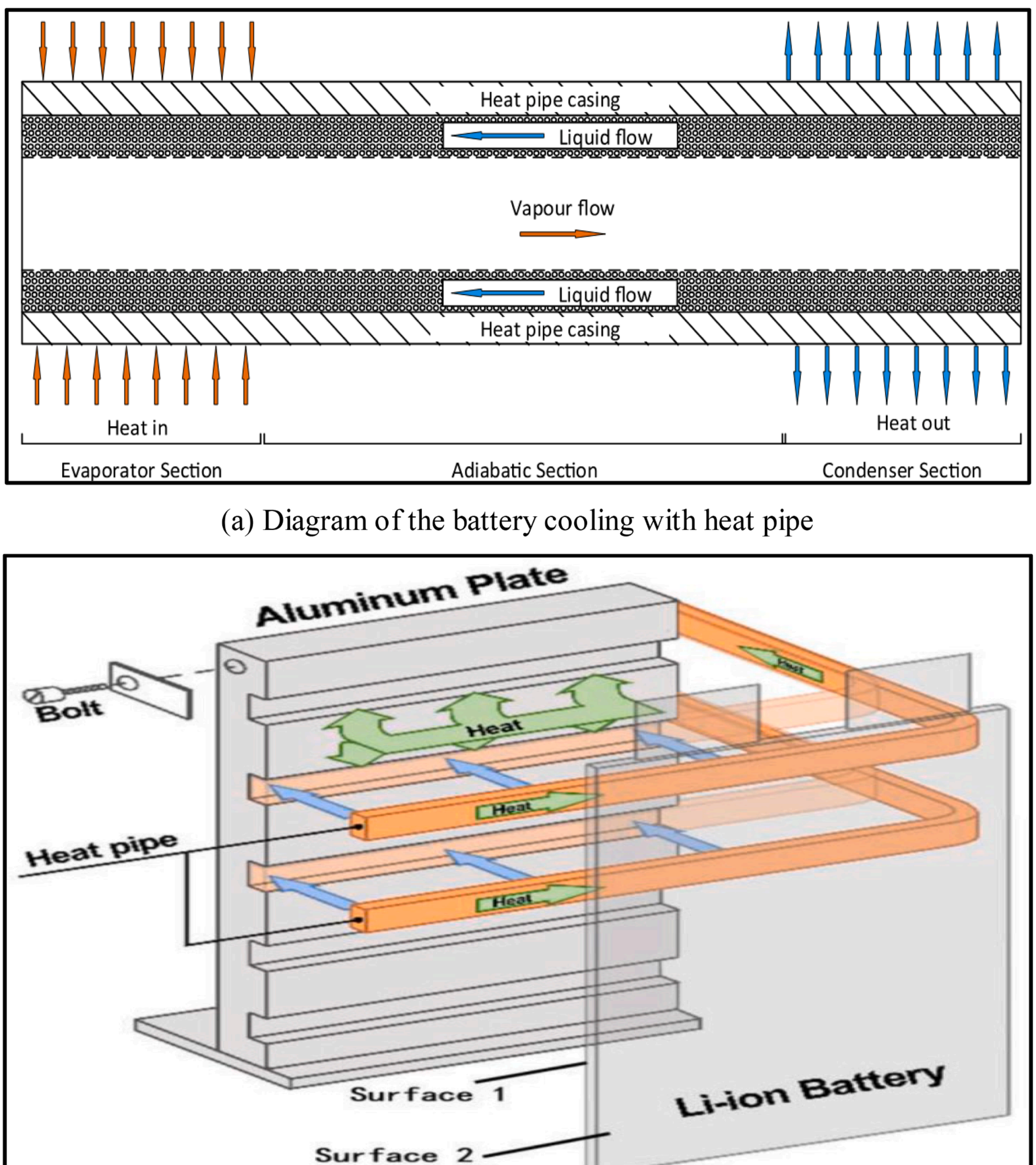

Fig. 18. Battery cooing with different heat pipe arrangements [247,248].

temperature within desired limits. The combination of heat pipes and PCM enhances thermal capabilities [235]. Various heat pipe designs and operational parameters, like flat heat pipes and micro heat pipes with PCM, aim to improve BTMS efficiency [236]. Integrating heat pipes in BTMS successfully regulates battery temperature and boosts energy density [237]. Research explores nanofluids and heat pipes to enhance thermal control of Li-ion batteries. Computational studies suggest increasing heat pipe diameter and quantity in BTMS can reduce battery temperature effectively [238]. Heat pipe cooling is a viable method for managing EV battery temperature, extracting heat efficiently to prevent overheating [239]. Heat pipes, including flat, pulsating, and micro heat pipes, are effective in BTMS for optimal battery operation [240]. Combining heat pipes with other cooling methods like liquid cooling or PCM further enhances BTMS thermal efficiency [241]. Various heat pipe configurations are explored to maximize BTMS cooling effectiveness [242]. In conclusion, heat pipe cooling offers a promising solution for BTMS, improving battery performance and lifespan in EVs [243,244]. Heat pipe cooling for BTM faces challenges in achieving uniform temperature distribution and improving thermal performance. Using heat pipes alone may not be enough, causing issues like decreased battery performance and safety concerns [245]. Combining heat pipes with other methods like PCM or liquid cooling is unlikely to lead to better temperature regulation and battery performance [246]. The selection of suitable heat pipe configurations, PCM types, and cooling fluid is crucial for optimal thermal management. The future of heat pipe cooling for BTM involves using multiple methods together to ensure continuous battery operation. Further research is needed to improve thermal regulation, increase energy density, and create effective cooling strategies for LIB packs in EVs. Fig. 18 shows battery cooing with different heat pipe arrangements.

4.6. Hybrid cooling

Hybrid cooling combines active and passive techniques to regulate temperature efficiently with minimal energy usage [249]. Several studies focus on using HCSs for BTM. Shyam Kumar [250] emphasized the importance of hybrid cooling for BTM and the need for further research on improving PCM properties. Seel [251] studied the effects of battery operation times and load profiles on temperature dynamics in a vanadium flow battery system, demonstrating the effectiveness of hybrid cooling [252]. HCSs are used for managing BT through active and passive cooling methods, showing better CP and energy efficiency compared to traditional methods. PCM combined with air cooling is a potential approach for BTM, while direct liquid cooling is studied for efficient battery temperature control. Hybrid TM strategies like metal fin intensified PCM systems aim to improve cooling and reduce power depletion, ensuring secure battery operation and enhancing EV performance. The design of active TMS, such as cooling ducts and air stream pressure, is crucial for maintaining safe BTs. Advanced techniques like direct liquid cooling are explored as hybrid cooling strategies for efficient BTM in EVs, aiming to address current cooling method limitations and ensure effective TM in normal and extreme conditions. HCSs face challenges in BTM due to inadequate TC and heat dissipation from PCMs [251]. Enhancing TC, thermal stability, and inflammable characteristics of PCMs is another challenge [212]. Using fuel components as coolants in liquid-cooled systems could potentially result in elevated energy consumption and CO_2 emissions. Implementing active cooling/heating for vanadium flow batteries requires considering battery operation times, load profiles, and climate conditions. Evaluation of cooling technologies like pulsating heat pipes is needed for different conditions and power inputs. Research and optimization are needed for the design and implementation of HCSs for BTM.

HCSs face challenges with BTM due to inadequate TC and heat dissipation by PCMs. Another challenge is enhancing TC, stability, and inflammability of PCMs [251]. Fuel components in liquid-cooled systems can increase energy consumption and emissions [212]. Active cooling in vanadium flow batteries needs consideration of operation times, load profiles, and climate. Evaluation of cooling technologies like heat pipes across various conditions is essential [253]. These challenges highlight the need for more research in HCSs for BTM. HCSs offer advantages like maintaining appropriate BT range and efficient cooling. PCM and metal fins in hybrid systems can improve CP and prevent PCM latent heat depletion [254]. Hybrid cooling helps maintain safe battery temperatures during high current periods. It also enhances EV performance and range by keeping batteries in optimal condition. Obstacles remain in improving TC, stability, and inflammability of PCM for BC [255]. Overall, HCSs have potential in enhancing battery thermal control but require further research for optimization.

Active cooling methods, like liquid cooling, offer efficient heat dissipation and precise temperature control, enhancing battery performance and longevity. However, they require electricity, leading to higher energy consumption and operational costs, and involve complex systems that need regular maintenance and can be prone to leaks and corrosion. On the other hand, passive cooling systems rely on natural convection, making them more energy-efficient and cost-effective as they don't require additional power. They are simpler, require less maintenance, and have lower long-term costs, but are less efficient in high-heat scenarios and provide less precise temperature control, which can impact battery performance in extreme conditions. Combining active and passive cooling methods can optimize performance by providing efficient heat dissipation, optimizing energy usage, and maintaining temperature stability. This hybrid approach also offers redundancy, ensuring reliability if one system fails. However, integrating both systems increases complexity, potentially leading to higher initial costs and more intricate maintenance requirements [256].

4.7. BTMS techniques and novel HT coolants

Various techniques for BTMS and coolants for HT have been studied. A water-CS with plate-fin heat sink was introduced by Patil et al. [257] to enhance cooling efficiency in LIB packs. Alnaqi [258] focused on nanofluids as coolants for Li-ion batteries, using a non-Newtonian water/CMC-CuO nanofluid. Yeranee and Rao [259] reviewed the use of TPMS in cooling channels for improved flow and HT, showing better thermal performance than conventional structures. Innovative coolants utilizing nanoparticles and hybrid nanofluids present enhanced effectiveness and cost-efficiency in comparison to conventional ones. These new coolants have higher thermal conductivity, specific heat, and density, enhancing their heat transfer capabilities [260]. They also show better energy efficiency and thermal performance in various systems, leading to enhanced cooling effectiveness [261]. The use of micro/nano roughened structures on aluminum heat sinks significantly boosts cooling capacity, lowering temperatures and thermal resistance [262]. Efficient cooling liquids like those containing castor oil produce adaptable, high-capacity, environmentally friendly solutions [263]. Overall, advancements in novel HT coolants offer promising solutions for achieving optimal conditions and improved performance in heating and cooling systems. Novel methods for managing battery thermal conditions and coolants in HT have pros and cons for electronic devices. Adding DFMS to BTMS could enhance cooling efficiency and decrease average BT and MT difference [264]. Liquid cooling, especially with nanofluids, shows promise for high heat electronic devices [263]. Liquid cooling is much more effective than air cooling but concerns like leakage need to be addressed. Serpentine Mini channel heat sinks can improve HT with increased pressure drop [265]. Chevron fins can reduce pressure drop and thermal resistance while enhancing HT. Optimization techniques can balance pressure drop and thermal resistance in BTMS design [266].

5. Conclusions

Efficient heat management is crucial for ensuring the optimal performance and safety of LIBs in EVs. This necessitates the adoption of innovative cooling solutions to effectively address the thermal challenges and aging effects associated with LIBs. The exploration of various thermal models, encompassing thermal abuse, EC, empirical, semi-empirical, and electrical models, holds significant importance in accurately predicting battery behavior and optimizing cooling strategies. Empirical models, relying on statistical analysis and data-driven methodologies, are essential in capturing observed data patterns. On the other hand, semi-empirical models deliver a synergistic combination of empirical data and theoretical principles, thereby improving predictive capabilities. By integrating advanced cooling techniques, such as PCM cooling and heat pipe cooling, with these models, substantial enhancements in battery management can be achieved. This leads to an extended remaining useful life of the battery and ensures the safety and efficiency of EVs. Key takeaways from this study include the categorization of LIBs based on their shape, size, and chemistry, as well as the identification of thermal challenges that necessitate effective TM in EVs. Thermal models play a pivotal role in predicting battery behavior, with thermal abuse, EC, empirical, semi-empirical, and electrical models providing a comprehensive understanding of LIBs under different conditions. The integration of advanced cooling techniques, such as air, liquid, PCM, heat pipe, and hybrid cooling systems, exhibits promising potential in mitigating thermal issues and enhancing LIB performance. Additionally, this review underscores the perils linked to excessive charging and discharging, which can lead to TR and irreversible capacity loss, respectively. In order to ensure thermal safety during overcharge cycling, it is crucial to implement safety measures such as preventing Li plating and controlling electrode-electrolyte interactions.

- The utilization of air coolant in BTMS provides a straightforward structure and maintenance, lightweight construction, low cost, and power consumption. However, the cooling efficiency is restricted due to the low TC and non-uniform temperature distribution.
- The implementation of liquid cooling in BTMS leads to a more even temperature distribution and improved cooling efficiency. However, this strategy necessitates the inclusion of more equipment, resulting in an intricate design, increased load, and additional expense.
- BTMS that utilizes PCM offers passive cooling without the need for extra equipment and ensures a uniform temperature distribution. However, this system's bulky nature and low TC result in lower cooling efficiency.
- BTMS assisted by heat pipes allows for the utilization of distinct types of fluid coolants and facilitates efficient HT. Nevertheless, the limited contact area with the battery restricts its performance.
- BTMS that relies solely on a pure HT coolant medium, has both advantages and disadvantages and is unable to effectively dissipate heat. Therefore, the recommended optimization technique is to combine multiple coolant media (hybrid coolants) for improved performance.
- Evaporative cooling, mist/spray cooling techniques, and the incorporation of nanoparticles into the coolant medium are identified as the most effective optimization strategies for HT coolant media. These approaches align with the future demands of BTMS in terms of high cooling efficiency, environmentally friendly and compact design, as well as low cost and power consumption.
- The environmental aspect plays a vital role in the design of EVs and BTM. Therefore, the utilization of hybrid coolants can be further enhanced by incorporating additional environmentally friendly, nontoxic, readily available, and cost-effective materials such as jute, pads, wick filters, and hydrophilic fibers.

The temperature dependence of Li-ion is commonly acknowledged as the most critical concern that impedes its utilization. Hence, it is crucial to establish a proficient BTMS to preserve the battery within the optimal temperature range. This investigation has undertaken an exhaustive evaluation of both traditional and innovative BTMS remedies, considering their selection of HT coolant medium and cooling methods. By means of simulations or laboratory experiments, each BTMS has been scrutinized, leading to subsequent deductions. Summarizing the effective TM is paramount for the optimal performance and safety of LIBs in EVs. By exploring various thermal models and incorporating advanced cooling techniques, we can improve battery management and extend the battery's remaining useful life. Categorizing LIBs based on shape, size, and chemistry and identifying thermal challenges are crucial for developing targeted cooling strategies. Additionally, implementing safety measures to prevent overcharging and over-discharging is essential for maintaining the thermal safety of the battery. Through these efforts, we can ensure the long-term performance and safety of LIBs in EVs.

Future scope of work

The future scope of work should emphasize the optimization of BTMS for LIBs in EVs. This can be accomplished by integrating innovative cooling methods like evaporative cooling, mist-spray cooling, and the application of nanoparticles in coolant media for improved HT efficiency. It is doubtful to further develop fast charging technologies that do not compromise battery life and safety. To achieve this, research into electrode kinetics and charging algorithms is imperative. Additionally, investigating prognostics to forecast the remaining useful life of battery systems may lead to enhanced system health management. To expedite and precisely design future battery technologies, advancements in computer simulation for system-level analysis of battery systems, encompassing mechanical, thermal, and electrical components, will be crucial.

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CRediT authorship contribution statement

Santosh Chavan: Writing – original draft, Methodology, Investigation, Conceptualization. **Bhumarapu Venkateswarlu:** Formal analysis, Data curation. **Mohammad Salman:** Formal analysis, Data curation. **Jie Liu:** Investigation, Formal analysis. **Prakash Pawar:** Investigation, Data curation. **Sang Woo Joo:** Writing – review & editing. **Gyu Sang Choi:** Writing – review & editing. **Sung Chul Kim:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] R.C. Wang, Y.C. Lin, S.H. Wu, A novel recovery process of metal values from the cathode active materials of the lithium-ion secondary batteries, Hydrometallurgy 99 (3–4) (2009) 194–201, https://doi.org/10.1016/J.HYDROMET.2009.08.005.

[2] V. Etacheri, R. Marom, R. Elazari, G. Salitra, D. Aurbach, Challenges in the development of advanced Li-ion batteries: a review, Energy Environ. Sci. 4 (9) (2011) 3243–3262, https://doi.org/10.1039/c1ee01598b.

[3] B. Scrosati, J. Hassoun, Y.K. Sun, Lithium-ion batteries. A look into the future, Energy Environ. Sci. 4 (9) (2011) 3287–3295, https://doi.org/10.1039/c1ee01388b.

[4] "Advanced energy materials - 2018 - Natarajan - burgeoning prospects of spent lithium-ion batteries in Multifarious.pdf".
[5] W. Gao, et al., Selective recovery of valuable metals from spent lithium-ion batteries – Process development and kinetics evaluation, J. Clean. Prod. 178 (2018) 833–845, https://doi.org/10.1016/j.jclepro.2018.01.040.
[6] J. Lin, et al., Conversion mechanisms of selective extraction of lithium from spent lithium-ion batteries by sulfation roasting, ACS Appl. Mater. Interfaces 12 (16) (2020) 18482–18489, https://doi.org/10.1021/acsami.0c00420.
[7] L. Li, et al., Succinic acid-based leaching system: a sustainable process for recovery of valuable metals from spent Li-ion batteries, J. Power Sources 282 (2015) 544–551, https://doi.org/10.1016/j.jpowsour.2015.02.073.
[8] Y. Yao, M. Zhu, Z. Zhao, B. Tong, Y. Fan, Z. Hua, Hydrometallurgical processes for recycling spent lithium-ion batteries: a critical review, ACS Sustain. Chem. Eng. 6 (11) (2018) 13611–13627, https://doi.org/10.1021/acssuschemeng.8b03545.
[9] I.Y.L. Hsieh, M.S. Pan, Y.M. Chiang, W.H. Green, Learning only buys you so much: practical limits on battery price reduction, Appl. Energy 239 (February) (2019) 218–224, https://doi.org/10.1016/j.apenergy.2019.01.138.
[10] E. Fan, et al., Sustainable recycling technology for Li-ion batteries and beyond: challenges and future prospects, Chem. Rev. 120 (14) (2020) 7020–7063, https://doi.org/10.1021/acs.chemrev.9b00535.
[11] H. Vikström, S. Davidsson, M. Höök, Lithium availability and future production outlooks, Appl. Energy 110 (2013) 252–266, https://doi.org/10.1016/j.apenergy.2013.04.005.
[12] S.A. Megahed, W.B. Ebner, Lithium-ion coin cells for electronic applications, in: Proc. Annu. Batter. Conf, 1994, pp. 129–134, https://doi.org/10.1109/bcaa.1994.283601.
[13] K. Karuppasamy, et al., Nonaqueous liquid electrolytes based on novel 1-ethyl-3-methylimidazolium bis (nonafluorobutane-1-sulfonyl imidate) ionic liquid for energy storage devices, J. Mater. Res. Technol. 9 (2) (2020) 1251–1260, https://doi.org/10.1016/j.jmrt.2019.11.052.
[14] J. Liao and Z. Ye, "Nontrivial effects of 'Trivial' parameters on the performance of lithium-sulfur batteries", doi: 10.3390/batteries4020022.
[15] "Advanced energy materials - 2017 - Esquivel - A metal-free and biotically degradable battery for portable Single-Use.pdf".
[16] S. Chen, et al., Critical parameters for evaluating coin cells and pouch cells of rechargeable Li-metal batteries, Joule 3 (4) (2019) 1094–1105, https://doi.org/10.1016/j.joule.2019.02.004.
[17] Y. Li, J. Song, J. Yang, A review on structure model and energy system design of lithium-ion battery in renewable energy vehicle, Renew. Sustain. Energy Rev. 37 (2014) 627–633, https://doi.org/10.1016/J.RSER.2014.05.059.
[18] A. Verma, A. Prajapati, D. Rakshit, A comparative study on prismatic and cylindrical lithium-ion batteries based on their performance in high ambient environment, J. Inst. Eng. Ser. C 103 (2) (2022) 149–166, https://doi.org/10.1007/S40032-021-00760-1/METRICS.
[19] R. Verrelli, B. Scrosati, Y.K. Sun, J. Hassoun, Stable, high voltage Li0.85Ni0.46Cu0.1Mn1.49O4 spinel cathode in a lithium-ion battery using a conversion-type CuO anode, ACS Appl. Mater. Interfaces 6 (7) (2014) 5206–5211, https://doi.org/10.1021/AM500499A.
[20] B. Kennedy, D. Patterson, S. Camilleri, Use of lithium-ion batteries in electric vehicles, J. Power Sources 90 (2) (2000) 156–162, https://doi.org/10.1016/S0378-7753(00)00402-X.
[21] H.M. Barkholtz, A. Fresquez, B.R. Chalamala, S.R. Ferreira, A database for comparative electrochemical performance of commercial 18650-format lithium-ion cells, J. Electrochem. Soc. 164 (12) (2017) A2697–A2706, https://doi.org/10.1149/2.1701712JES.
[22] B. Diouf, R. Pode, Potential of lithium-ion batteries in renewable energy, Renew. Energy 76 (2015) 375–380, https://doi.org/10.1016/J.RENENE.2014.11.058.
[23] D. Li, X. Li, X. Hou, X. Sun, B. Liu, D. He, Building a Ni3S2 nanotube array and investigating its application as an electrode for lithium ion batteries, Chem. Commun. 50 (66) (2014) 9361–9364, https://doi.org/10.1039/C4CC01311E.
[24] Y. Wang, A review on rectangular lithium ion batteries: progress and prospects, Renew. Sustain. Energy Rev. 81 (2018) 3119–3133.
[25] M. Dethon, The development of rectangular Li-ion cells for automotive applications, J. Energy Storage 6 (2016) 116–123.
[26] Y. Kim, Lithium nickel cobalt manganese oxide synthesized using alkali chloride flux: morphology and performance as a cathode material for lithium ion batteries, ACS Appl. Mater. Interfaces 4 (5) (2012) 2329–2333, https://doi.org/10.1021/AM300386J.
[27] M.S. Patil, S. Panchal, N. Kim, M.Y. Lee, Cooling performance characteristics of 20 Ah lithium-ion pouch cell with cold plates along both surfaces, Energies 11 (10) (2018), https://doi.org/10.3390/EN11102550.
[28] P.Y. Chen, et al., Selective permeable lithium-ion channels on lithium metal for practical lithium-sulfur pouch cells, Angew. Chemie 60 (33) (2021) 18031–18036, https://doi.org/10.1002/ANIE.202101958.
[29] X. Zhao, M. Li, K.H. Chang, Y.M. Lin, Composites of graphene and encapsulated silicon for practically viable high-performance lithium-ion batteries, Nano Res. 7 (10) (2014) 1429–1438, https://doi.org/10.1007/S12274-014-0463-6.
[30] Y. Li, et al., Single atom array mimic on ultrathin MOF nanosheets boosts the safety and life of lithium–sulfur batteries, Adv. Mater. 32 (8) (2020), https://doi.org/10.1002/ADMA.201906722.
[31] S. Hauswald, A. Sprenker, The pouch cell—A versatile and efficient battery system, JOM 78 (8) (2020) 1965–1976.
[32] Z. Chang, et al., Rechargeable Li//Br battery: a promising platform for post lithium ion batteries, J. Mater. Chem. 2 (45) (2014) 19444–19450, https://doi.org/10.1039/C4TA04419C.
[33] X. Liu, Y. Xie, P. Peng, X. Sun, A review of lithium-ion prismatic cells and packs for large-scale applications, Front. Energy 12 (2) (2018) 184–195.
[34] W. Infante, J. Ma, A. Liebman, Operational strategy analysis of electric vehicle battery swapping stations, IET Electr. Syst. Transp. 8 (2) (2018) 130–135, https://doi.org/10.1049/IET-EST.2017.0075.
[35] J. Leadbetter, L.G. Swan, Selection of battery technology to support grid-integrated renewable electricity, J. Power Sources 216 (2012) 376–386, https://doi.org/10.1016/J.JPOWSOUR.2012.05.081.
[36] A. Iavarone, et al., Dysexecutive performance of healthy oldest old subjects on the frontal assessment battery, Aging Clin. Exp. Res. 23 (5–6) (2011) 351–356, https://doi.org/10.3275/7809.
[37] J. Neubauer and M. Simpson, "Deployment of behind-the-meter energy storage for demand charge reduction," Jan. 2015, doi: 10.2172/1168774.
[38] Y. Preger, et al., Degradation of commercial lithium-ion cells as a function of chemistry and cycling conditions, J. Electrochem. Soc. 167 (12) (2020) 120532, https://doi.org/10.1149/1945-7111/abae37.
[39] J. Xie, Y.C. Lu, A retrospective on lithium-ion batteries, Nat. Commun. 11 (1) (2020) 9–12, https://doi.org/10.1038/s41467-020-16259-9.
[40] J.M. Tarascon, M. Armand, Issues and challenges facing rechargeable lithium batteries, Nature 414 (6861) (2001) 359–367, https://doi.org/10.1038/35104644.
[41] M. Armand, J.M. Tarascon, Building better batteries, Nat. 451 (7179) (2008) 652–657, https://doi.org/10.1038/451652a, 2008 4517179.
[42] M. Li, J. Lu, Z. Chen, K. Amine, 30 Years of lithium-ion batteries, Adv. Mater. 30 (33) (2018) 1800561, https://doi.org/10.1002/ADMA.201800561.
[43] X. Cao, et al., Stability of solid electrolyte interphases and calendar life of lithium metal batteries, Energy Environ. Sci. (2023) 1548–1559, https://doi.org/10.1039/d2ee03557j.
[44] J.W. Fergus, Recent developments in cathode materials for lithium ion batteries, J. Power Sources 195 (4) (2010) 939–954, https://doi.org/10.1016/J.JPOWSOUR.2009.08.089.
[45] M.R. Palacín, Recent advances in rechargeable battery materials: a chemist's perspective, Chem. Soc. Rev. 38 (9) (2009) 2565–2575, https://doi.org/10.1039/B820555H.
[46] K. Wang, et al., Recent advances and historical developments of high voltage lithium cobalt oxide materials for rechargeable Li-ion batteries, J. Power Sources 460 (2020) 228062, https://doi.org/10.1016/J.JPOWSOUR.2020.228062.
[47] K. Amine, et al., Factors responsible for impedance rise in high power lithium ion batteries, J. Power Sources 97–98 (2001) 684–687, https://doi.org/10.1016/S0378-7753(01)00701-7.
[48] D.P. Abraham, et al., Microscopy and spectroscopy of lithium nickel oxide-based particles used in high power lithium-ion cells, J. Electrochem. Soc. 150 (11) (2003) A1450, https://doi.org/10.1149/1.1613291.
[49] I. Belharouak, W. Lu, D. Vissers, K. Amine, Safety characteristics of Li (Ni0.8Co0.15Al 0.05)O2 and Li(Ni1/3Co1/3Mn 1/3)O2, Electrochem. Commun. 8 (2) (2006) 329–335, https://doi.org/10.1016/j.elecom.2005.12.007.
[50] D.H. Doughty, E.P. Roth, C.C. Crafts, G. Nagasubramanian, G. Henriksen, K. Amine, Effects of additives on thermal stability of Li ion cells, J. Power Sources 146 (1–2) (2005) 116–120, https://doi.org/10.1016/j.jpowsour.2005.03.170.
[51] X. Liu, C. Chen, Y. Zhao, B. Jia, A review on the synthesis of manganese oxide nanomaterials and their applications on lithium-ion batteries, J. Nanomater. 2013 (2013), https://doi.org/10.1155/2013/736375.
[52] Z. Zhu, M. Wang, Y. Meng, Z. Lin, Y. Cui, and W. Chen, "A high-rate lithium manganese oxide-hydrogen battery," 2020, doi: 10.1021/acs.nanolett.0c00044.
[53] M. Rossouw, A. de Kock, L. de Picciotto, M. Thackeray, W. David, R. Ibberson, Structural aspects of lithium-manganese-oxide electrodes for rechargeable lithium batteries, Mater. Res. Bull. 25 (2) (1990) 173–182, https://doi.org/10.1016/0025-5408(90)90043-2.
[54] M.M. Thackeray, Manganese oxides for lithium batteries, Prog. Solid State Chem. 25 (1–2) (1997) 1–71, https://doi.org/10.1016/S0079-6786(97)81003-5.
[55] M. Rossouw, M. Thackeray, Lithium manganese oxides from Li2MnO3 for rechargeable lithium battery applications, Mater. Res. Bull. 26 (6) (1991) 463–473, https://doi.org/10.1016/0025-5408(91)90186-P.
[56] J. Zhao, Z. Tao, J. Liang, J. Chen, Facile synthesis of nanoporous γ-MnO2 structures and their application in rechargeable Li-ion batteries, Cryst. Growth Des. 8 (8) (2008) 2799–2805, https://doi.org/10.1021/CG701044B.
[57] M.M. Thackeray, C.S. Johnson, J.T. Vaughey, N. Li, S.A. Hackney, Advances in manganese- oxide 'composite' electrodes for lithium-ion batteries, J. Mater. Chem. 15 (23) (2005) 2257–2267, https://doi.org/10.1039/B417616M.
[58] M.M. Thackeray, W.I.F. David, P.G. Bruce, J.B. Goodenough, Lithium insertion into manganese spinels, Mater. Res. Bull. 18 (4) (1983) 461–472, https://doi.org/10.1016/0025-5408(83)90138-1.
[59] J.M. Tarascon, D. Guyomard, New electrolyte compositions stable over the 0 to 5 V voltage range and compatible with the Li1+xMn2O4/carbon Li-ion cells, Solid State Ion. 69 (3–4) (1994) 293–305, https://doi.org/10.1016/0167-2738(94)90418-9.
[60] B. Kennedy, D. Patterson, S. Camilleri, Use of lithium-ion batteries in electric vehicles, J. Power Sources 90 (2) (2000) 156–162, https://doi.org/10.1016/S0378-7753(00)00402-X.
[61] G. Nagasubramanian, D. Ingersoll, D. Doughty, D. Radzykewycz, C. Hill, C. Marsh, Electrical and electrochemical performance characteristics of large capacity lithium-ion cells, J. Power Sources 80 (1) (1999) 116–118, https://doi.org/10.1016/S0378-7753(98)00255-9.
[62] J.M. Tarascon, et al., Hunting for better Li-based electrode materials via low temperature inorganic synthesis, Chem. Mater. 22 (3) (2010) 724–739, https://doi.org/10.1021/cm9030478.

[63] A.K. Padhi, J.B. Goodenough, Phospho-olivines as positive-electrodematerials forrechargeable lithium batteries, J. Electroanal. Chem 144 (4) (1997) 16.
[64] M. Takahashi, S. ichi Tobishima, K. Takei, Y. Sakurai, Reaction behavior of LiFePO4 as a cathode material for rechargeable lithium batteries, Solid State Ion. 148 (3–4) (2002) 283–289, https://doi.org/10.1016/S0167-2738(02)00064-4.
[65] L.X. Yuan, et al., Development and challenges of LiFePO4 cathode material for lithium-ion batteries, Energy Environ. Sci. 4 (2) (2011) 269–284, https://doi.org/10.1039/c0ee00029a.
[66] Y. Zhang, et al., Advances in new cathode material LiFePO 4 for lithium-ion batteries, Synth. Met. 162 (13–14) (2012) 1315–1326, https://doi.org/10.1016/j.synthmet.2012.04.025.
[67] X. Wang, X. Wang, R. Zhang, Y. Wang, H. Shu, Hydrothermal preparation and performance of LiFePO4 by using Li3PO4 recovered from spent cathode scraps as Li source, Waste Manag. 78 (2018) (2018) 208–216, https://doi.org/10.1016/j.wasman.2018.05.029.
[68] T. Elwert, Q. Hua, K. Schneider, Recycling of lithium iron phosphate batteries: future prospects and research needs, Mater. Sci. Forum 959 MSF (2019) 49–68, https://doi.org/10.4028/www.scientific.net/MSF.959.49.
[69] J. Wang, Z. Sun, X. Wei, Performance and characteristic research in LiFePO4 battery for electric vehicle applications, in: 5th IEEE Veh. Power Propuls. Conf. VPPC '09 4, 2009, pp. 1657–1661, https://doi.org/10.1109/VPPC.2009.5289664.
[70] Z. Lu et al., "Layered Li[Nix Co1−2x Mnx]O2 cathode materials for lithium-ion batteries service Layered Li † Ni x Co 1 À 2 x Mn x ‡ O 2 Cathode Materials for," vol. 4, no. 12, pp. 4–8, 2001, doi: 10.1149/1.1413182.
[71] S.D. William Gourley, T. Or, Z. Chen, iScience breaking free from cobalt reliance in lithium-ion batteries, ISCIENCE 23 (2020) 101505, https://doi.org/10.1016/j.isci.
[72] A. Zeng, et al., Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages, Nat. Commun. 13 (1) (2022) 1–11, https://doi.org/10.1038/S41467-022-29022-Z.
[73] C.P. Sandhya, B. John, C. Gouri, Lithium titanate as anode material for lithium-ion cells: a review, Ionics (Kiel) 20 (5) (2014) 601–620, https://doi.org/10.1007/s11581-014-1113-4.
[74] P. Huang, Q. Wang, K. Li, P. Ping, J. Sun, The combustion behavior of large scale lithium titanate battery, Sci. Rep. 5 (1) (2015) 1–12, https://doi.org/10.1038/srep07788. *2015 51*.
[75] Y. Yang, et al., Lithium titanate tailored by cathodically induced graphene for an ultrafast lithium ion battery, Adv. Funct. Mater. 24 (27) (2014) 4349–4356, https://doi.org/10.1002/ADFM.201304263.
[76] Z. Choi, D. Kramer, R. Mönig, Correlation of stress and structural evolution in Li4Ti 5O12-based electrodes for lithium ion batteries, J. Power Sources 240 (2013) 245–251, https://doi.org/10.1016/j.jpowsour.2013.03.185.
[77] S.C.L. Koh, et al., Higher 2nd life lithium titanate battery content in hybrid energy storage systems lowers environmental-economic impact and balances eco-efficiency, Renew. Sustain. Energy Rev. 152 (2021) 111704, https://doi.org/10.1016/J.RSER.2021.111704.
[78] N. Nitta, F. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: present and future, Mater. Today 18 (5) (2015) 252–264, https://doi.org/10.1016/j.mattod.2014.10.040.
[79] International Energy Agency (IEA), Global EV outlook 2022 - Securing supplies for an electric future, Glob. EV Outlook (2022) 221, 2022[Online]. Available: https://www.iea.org/reports/global-ev-outlook-2022%0Ahttps://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf.
[80] "Electric vehicles: what's next VII: confronting greenflation." Accessed: Aug. 09, 2023. [Online]. Available: https://www.goldmansachs.com/intelligence/pages/electric-vehicles-whats-next-vii-confronting-greenflation.html.
[81] D. Zhang, C. Tan, T. Ou, S. Zhang, L. Li, X. Ji, Constructing advanced electrode materials for low-temperature lithium-ion batteries: a review, Energy Rep. 8 (2022) 4525–4534, https://doi.org/10.1016/J.EGYR.2022.03.130.
[82] J. Hou, et al., Fundamentals and challenges of lithium ion batteries at temperatures between −40 and 60 °C, Adv. Energy Mater. 10 (18) (2020) 1904152, https://doi.org/10.1002/AENM.201904152.
[83] N. Meyer, I. Whittal, M. Christenson, and A. Loiselle-Lapointe, "The impact of driving cycle and climate on electrical consumption & range of fully electric passenger vehicles," 2012.
[84] "The impact of driving cycle and climate on electrical consumption & range of fully electric passenger vehicles." Accessed: Mar. 04, 2024. [Online]. Available: https://tc.canada.ca/en/programs/non-funding-programs/ecotechnology-vehicles-program/impact-driving-cycle-climate-electrical-consumption-range-fully-electric-passenger-vehicles.
[85] J. Jaguemont, L. Boulon, Y. Dubé, D. Poudrier, Low temperature discharge cycle tests for a lithium ion cell, in: 2014 IEEE Veh. Power Propuls. Conf. VPPC 2014, 2014, https://doi.org/10.1109/VPPC.2014.7007097.
[86] J.P. Singer, K.P. Birke, Kinetic study of low temperature capacity fading in Li-ion cells, J. Energy Storage 13 (2017) 129–136, https://doi.org/10.1016/J.EST.2017.07.002.
[87] Q. Li, G. Liu, H. Cheng, Q. Sun, J. Zhang, J. Ming, Low-temperature electrolyte design for lithium-ion batteries: prospect and challenges, Chem. – A Eur. J. 27 (64) (2021) 15842–15865, https://doi.org/10.1002/CHEM.202101407.
[88] N. Zhang, et al., Critical review on low-temperature Li-ion/metal batteries, Adv. Mater. 34 (15) (2022) 2107899, https://doi.org/10.1002/ADMA.202107899.
[89] B. Ashok, et al., Towards safer and smarter design for lithium-ion-battery-powered electric vehicles: a comprehensive review on control strategy architecture of battery management system, Energies 15 (12) (2022) 4227, https://doi.org/10.3390/EN15124227, 2022*Vol. 15, Page 4227*.
[90] N. Piao, et al., Challenges and development of lithium-ion batteries for low temperature environments, eTransportation 11 (2022) 100145, https://doi.org/10.1016/J.ETRAN.2021.100145.
[91] Z. Chen, Y. Qin, K. Amine, Y.K. Sun, Role of surface coating on cathode materials for lithium-ion batteries, J. Mater. Chem. 20 (36) (2010) 7606–7612, https://doi.org/10.1039/C0JM00154F.
[92] P. Guan, et al., Recent progress of surface coating on cathode materials for high-performance lithium-ion batteries, J. Energy Chem. 43 (2020) 220–235, https://doi.org/10.1016/J.JECHEM.2019.08.022.
[93] P.G. Bruce, B. Scrosati, J.M. Tarascon, Nanomaterials for rechargeable lithium batteries, Angew. Chemie Int. Ed. 47 (16) (2008) 2930–2946, https://doi.org/10.1002/ANIE.200702505.
[94] L.J. Zeng, Q. Gong, X.Z. Liao, L. He, Y.S. He, Z.F. Ma, Enhanced low-temperature performance of slight Mn-substituted LiFePO4/C cathode for lithium ion batteries, Chin. Sci. Bull. 56 (12) (2011) 1262–1266, https://doi.org/10.1007/S11434-010-4097-0/METRICS.
[95] Q.B. Liu, S.J. Liao, H.Y. Song, Z.X. Liang, High-performance LiFePO4/C materials: effect of carbon source on microstructure and performance, J. Power Sources 211 (2012) 52–58, https://doi.org/10.1016/J.JPOWSOUR.2012.03.090.
[96] Y. Yin, et al., High-rate capability of LiFePO4 cathode materials containing Fe2P and trace carbon, J. Power Sources 199 (2012) 256–262, https://doi.org/10.1016/J.JPOWSOUR.2011.10.042.
[97] D. Xie, et al., The low temperature electrochemical performances of LiFePO4/C/graphene nanofiber with 3D-bridge network structure, Electrochim. Acta 217 (2016) 62–72, https://doi.org/10.1016/J.ELECTACTA.2016.09.058.
[98] G. Wu, et al., A hydrothermally synthesized LiFePO4/C composite with superior low-temperature performance and cycle life, Appl. Surf. Sci. 435 (2018) 1329–1336, https://doi.org/10.1016/J.APSUSC.2017.11.276.
[99] W. Duan, et al., Superior electrochemical performance of a novel LiFePO4/C/CNTs composite for aqueous rechargeable lithium-ion batteries, Phys. Chem. Chem. Phys. 22 (4) (2020) 1953–1962, https://doi.org/10.1039/C9CP06042A.
[100] J. Lin, X. Zhang, E. Fan, R. Chen, F. Wu, L. Li, Carbon neutrality strategies for sustainable batteries: from structure, recycling, and properties to applications, Energy Environ. Sci. 16 (3) (2023) 745–791, https://doi.org/10.1039/D2EE03257K.
[101] A.K. Nandi, D.P. Chatterjee, Hybrid polymer gels for energy applications, J. Mater. Chem. A 11 (24) (2023) 12593–12642, https://doi.org/10.1039/D2TA09525D.
[102] L. Fagiolari, et al., Integrated energy conversion and storage devices: interfacing solar cells, batteries and supercapacitors, Energy Storage Mater 51 (2022) 400–434, https://doi.org/10.1016/J.ENSM.2022.06.051.
[103] G. Cai, et al., Enhanced low temperature electrochemical performances of LiFePO4/C by surface modification with Ti3SiC2, J. Power Sources 288 (2015) 136–144, https://doi.org/10.1016/J.JPOWSOUR.2015.04.129.
[104] A. Liu, et al., A degradable membrane based on lignin-containing cellulose for high-energy lithium-ion batteries, Int. J. Biol. Macromol. 213 (2022) 690–698, https://doi.org/10.1016/J.IJBIOMAC.2022.06.004.
[105] Z. Huang, P. Luo, H. Zheng, Design of Ti4+-doped Li3V2(PO4)3/C fibers for lithium energy storage, Ceram. Int. 48 (6) (2022) 8325–8330, https://doi.org/10.1016/J.CERAMINT.2021.12.037.
[106] X.H. Rui, Y. Jin, X.Y. Feng, L.C. Zhang, C.H. Chen, A comparative study on the low-temperature performance of LiFePO4/C and Li3V2(PO4)3/C cathodes for lithium-ion batteries, J. Power Sources 196 (4) (2011) 2109–2114, https://doi.org/10.1016/J.JPOWSOUR.2010.10.063.
[107] M. Liang, et al., Ru- and Cl-Co doped Li3V2(PO4)3 with enhanced performance for lithium-ion batteries in a wide temperature range, Small 18 (29) (2022) 2202151, https://doi.org/10.1002/SMLL.202202151.
[108] G. Cai, et al., Synthesis and low temperature electrochemical properties of CeO2 and C co-modified Li3V2(PO4)3 cathode materials for lithium-ion batteries, Electrochim. Acta 174 (2015) 1131–1140, https://doi.org/10.1016/J.ELECTACTA.2015.06.097.
[109] A. Manthiram, A reflection on lithium-ion battery cathode chemistry, Nat. Commun. 11 (1) (2020) 1–9, https://doi.org/10.1038/s41467-020-15355-0. *2020 111*.
[110] S.T. Myung, et al., Nickel-rich layered cathode materials for automotive lithium-ion batteries: achievements and perspectives, ACS Energy Lett 2 (1) (2017) 196–223, https://doi.org/10.1021/ACSENERGYLETT.6B00594/ASSET/IMAGES/LARGE/NZ-2016-00594B_0017.JPEG.
[111] Z. Li, et al., Effect of Ti doping on LiFePO4/C cathode material with enhanced low-temperature electrochemical performance, Ionics (Kiel) 26 (4) (2020) 1599–1609, https://doi.org/10.1007/S11581-019-03408-4/METRICS.
[112] Y. Zhao, L. Peng, B. Liu, G. Yu, Single-crystalline LiFePO4 nanosheets for high-rate Li-ion batteries, Nano Lett. 14 (5) (2014) 2849–2853, https://doi.org/10.1021/NL5008568/SUPPL_FILE/NL5008568_SI_001.PDF.
[113] G. Geng, et al., Effect of particle size of FePO4•2H2O on the physical and electrochemical properties of LiFePO4/C cathode for LIBs, Int. J. Electrochem. Sci. 17 (7) (2022) 220722, https://doi.org/10.20964/2022.07.14.
[114] F. Teng, et al., Hydrothermal synthesis of plate-like carbon-coated Li3V2(PO4)3 and its low temperature performance for high power lithium ion batteries, Electrochim. Acta 91 (2013) 43–49, https://doi.org/10.1016/J.ELECTACTA.2012.12.090.
[115] Y. Li, et al., Past, present and future of high-nickel materials, Nano Energy 119 (2024) 109070, https://doi.org/10.1016/J.NANOEN.2023.109070.

[116] L. Chang, et al., A review on nickel-rich nickel–cobalt–manganese ternary cathode materials LiNi0.6Co0.2Mn0.2O2 for lithium-ion batteries: performance enhancement by modification, Mater. Horizons 10 (11) (2023) 4776–4826, https://doi.org/10.1039/D3MH01151H.
[117] S.-J. Yoon, S.-T. Myung, Y.-K. Sun, Low temperature electrochemical properties of Li[Ni x Co y Mn 1-x-y]O 2 cathode materials for lithium-ion batteries, J. Electrochem. Soc. 161 (10) (2014) A1514–A1520, https://doi.org/10.1149/2.0121410JES/XML.
[118] K. Hasan, N. Tom, M.R. Yuce, Navigating battery choices in IoT: an extensive survey of technologies and their applications, Batter 9 (12) (2023) 580, https://doi.org/10.3390/BATTERIES9120580, 2023*Vol. 9, Page 580*.
[119] A. Belgibayeva, et al., Synthesis of free-standing tin phosphide/phosphate carbon composite nanofibers as anodes for lithium-ion batteries with improved low-temperature performance, Small 19 (48) (2023) 2304062, https://doi.org/10.1002/SMLL.202304062.
[120] R. Akolkar, Modeling dendrite growth during lithium electrodeposition at sub-ambient temperature, J. Power Sources 246 (2014) 84–89, https://doi.org/10.1016/J.JPOWSOUR.2013.07.056.
[121] N. Zhao, et al., Fe3+-stabilized Ti3C2Tx MXene enables ultrastable Li-ion storage at low temperature, J. Mater. Sci. Technol. 67 (2021) 156–164, https://doi.org/10.1016/J.JMST.2020.06.037.
[122] A. Senyshyn, M.J. Mühlbauer, O. Dolotko, H. Ehrenberg, Low-temperature performance of Li-ion batteries: the behavior of lithiated graphite, J. Power Sources 282 (2015) 235–240, https://doi.org/10.1016/J.JPOWSOUR.2015.02.008.
[123] Z. Bai, et al., Two-dimensional NiO@C-N nanosheets composite as a superior low-temperature anode material for advanced lithium-/sodium-ion batteries, ChemElectroChem 7 (17) (2020) 3616–3622, https://doi.org/10.1002/CELC.202000747.
[124] G. Park, N. Gunawardhana, H. Nakamura, Y.S. Lee, M. Yoshio, The study of electrochemical properties and lithium deposition of graphite at low temperature, J. Power Sources 199 (2012) 293–299, https://doi.org/10.1016/J.JPOWSOUR.2011.10.058.
[125] Z.N. Ezhyeh, M. Khodaei, F. Torabi, Review on doping strategy in Li4Ti5O12 as an anode material for lithium-ion batteries, Ceram. Int. 49 (5) (2023) 7105–7141, https://doi.org/10.1016/J.CERAMINT.2022.04.340.
[126] B. Hu, et al., Excellent rate and low temperature performance of lithium-ion batteries based on binder-free Li4Ti5O12 electrode, ChemElectroChem 7 (3) (2020) 716–722, https://doi.org/10.1002/CELC.201901914.
[127] L. Tan, et al., Subzero temperature promotes stable lithium storage in SnO2, Energy Storage Mater. 36 (2021) 242–250, https://doi.org/10.1016/J.ENSM.2020.12.033.
[128] S. Goutam, N. Omar, P. Van Den Bossche, J. Van Mierlo, Review of nanotechnology for anode materials in batteries, Emerg. Nanotechnol. Recharg. Energy Storage Syst. (2017) 45–82, https://doi.org/10.1016/B978-0-323-42977-1.00002-9.
[129] H. peng Feng, et al., Core-shell nanomaterials: applications in energy storage and conversion, Adv. Colloid Interface Sci. 267 (2019) 26–46, https://doi.org/10.1016/J.CIS.2019.03.001.
[130] X. Hui, R. Zhao, P. Zhang, C. Li, C. Wang, L. Yin, Low-temperature reduction strategy synthesized Si/Ti3C2 MXene composite anodes for high-performance Li-ion batteries, Adv. Energy Mater. 9 (33) (2019) 1901065, https://doi.org/10.1002/AENM.201901065.
[131] Z. Wang, W. Han, Q. Kuang, Q. Fan, Y. Zhao, Low-temperature synthesis of CeB6 nanowires and nanoparticles as feasible lithium-ion anode materials, Adv. Powder Technol. 31 (2) (2020) 595–603, https://doi.org/10.1016/J.APT.2019.11.014.
[132] L. qiang Yu, S.X. Zhao, Y. Yuan, G.D. Wei, Improving the room/low-temperature performance of VS4 anode by regulating the sulfur vacancy and microstructure, Electrochim. Acta 384 (2021) 138351, https://doi.org/10.1016/J.ELECTACTA.2021.138351.
[133] J. Xu, et al., High-energy lithium-ion batteries: recent progress and a promising future in applications, Energy Environ. Mater. 6 (5) (2023) e12450, https://doi.org/10.1002/EEM2.12450.
[134] P.U. Nzereogu, A.D. Omah, F.I. Ezema, E.I. Iwuoha, A.C. Nwanya, Anode materials for lithium-ion batteries: a review, Appl. Surf. Sci. Adv. 9 (2022) 100233, https://doi.org/10.1016/J.APSADV.2022.100233.
[135] S. Li, et al., Fast charging anode materials for lithium-ion batteries: current status and perspectives, Adv. Funct. Mater. 32 (23) (2022) 2200796, https://doi.org/10.1002/ADFM.202200796.
[136] Q. Meng, F. Chen, Q. Hao, N. Li, X. Sun, Nb-doped Li4Ti5O12-TiO2 hierarchical microspheres as anode materials for high-performance Li-ion batteries at low temperature, J. Alloys Compd. 885 (2021) 160842, https://doi.org/10.1016/J.JALLCOM.2021.160842.
[137] Z. Gao, X. Zhang, H. Hu, D. Guo, H. Zhao, H. Yu, Influencing factors of low- and high-temperature behavior of Co-doped Zn2SnO4–graphene–carbon nanocomposite as anode material for lithium-ion batteries, J. Electroanal. Chem. 791 (2017) 56–63, https://doi.org/10.1016/J.JELECHEM.2017.03.020.
[138] M. Zou, et al., Silver-incorporated composites of Fe2O3 carbon nanofibers as anodes for high-performance lithium batteries, J. Power Sources 270 (2014) 468–474, https://doi.org/10.1016/J.JPOWSOUR.2014.07.119.
[139] J. Li, W. Wen, G. Xu, M. Zou, Z. Huang, L. Guan, Fe-added Fe3C carbon nanofibers as anode for Li ion batteries with excellent low-temperature performance, Electrochim. Acta 153 (2015) 300–305, https://doi.org/10.1016/J.ELECTACTA.2014.12.008.
[140] Y. Saito, M. Shikano, H. Kobayashi, Heat generation behavior during charging and discharging of lithium-ion batteries after long-time storage, J. Power Sources 244 (2013) 294–299, https://doi.org/10.1016/J.JPOWSOUR.2012.12.124.
[141] Q. Zhang, et al., Research on the reversible and irreversible heat generation of LiNi1−x−yCoxMnyO2-based lithium-ion batteries, Fire Technol. 59 (3) (2023) 1029–1049, https://doi.org/10.1007/S10694-022-01220-7/METRICS.
[142] T.M. Bandhauer, S. Garimella, T.F. Fuller, A critical review of thermal issues in lithium-ion batteries, J. Electrochem. Soc. 158 (3) (2011) R1. Jan.Accessed: Apr. 14, 2023. [Online]. Available, https://iopscience.iop.org/article/10.1149/1.3515880.
[143] R. Zhao, J. Gu, J. Liu, An investigation on the significance of reversible heat to the thermal behavior of lithium ion battery through simulations, J. Power Sources 266 (2014) 422–432, https://doi.org/10.1016/J.JPOWSOUR.2014.05.034.
[144] M. Balasundaram, V. Ramar, C. Yap, L. Lu, A.A.O. Tay, B. Palani, Heat loss distribution: impedance and thermal loss analyses in LiFePO4/graphite 18650 electrochemical cell, J. Power Sources 328 (2016) 413–421, https://doi.org/10.1016/J.JPOWSOUR.2016.08.045.
[145] A. Swiderska-Mocek, E. Rudnicka, A. Lewandowski, Temperature coefficients of Li-ion battery single electrode potentials and related entropy changes – revisited, Phys. Chem. Chem. Phys. 21 (4) (2019) 2115–2120, https://doi.org/10.1039/C8CP06638H.
[146] A. Nazari, S. Farhad, Heat generation in lithium-ion batteries with different nominal capacities and chemistries, Appl. Therm. Eng. 125 (2017) 1501–1517, https://doi.org/10.1016/J.APPLTHERMALENG.2017.07.126.
[147] C. Te Hsieh, C.T. Pai, Y.F. Chen, P.Y. Yu, R.S. Juang, Electrochemical performance of lithium iron phosphate cathodes at various temperatures, Electrochim. Acta 115 (2014) 96–102, https://doi.org/10.1016/J.ELECTACTA.2013.10.082.
[148] X. Chen, et al., Mixed salts of LiTFSI and LiBOB for stable LiFePO4-based batteries at elevated temperatures, J. Mater. Chem. A 2 (7) (2014) 2346–2352, https://doi.org/10.1039/C3TA13043F.
[149] T. Kurita, et al., Challenges toward higher temperature operation of LiFePO4, J. Power Sources 214 (2012) 166–170, https://doi.org/10.1016/J.JPOWSOUR.2012.04.073.
[150] Q. Hu, et al., Graft copolymer-based lithium-ion battery for high-temperature operation, J. Power Sources 196 (13) (2011) 5604–5610, https://doi.org/10.1016/J.JPOWSOUR.2011.03.001.
[151] M. Dahbi, F. Ghamouss, F. Tran-Van, D. Lemordant, M. Anouti, Comparative study of EC/DMC LiTFSI and LiPF6 electrolytes for electrochemical storage, J. Power Sources 196 (22) (2011) 9743–9750, https://doi.org/10.1016/J.JPOWSOUR.2011.07.071.
[152] B. Ravdel, K.M. Abraham, R. Gitzendanner, J. DiCarlo, B. Lucht, C. Campion, Thermal stability of lithium-ion battery electrolytes, J. Power Sources 119–121 (2003) 805–810, https://doi.org/10.1016/S0378-7753(03)00257-X.
[153] S.J. An, J. Li, C. Daniel, D. Mohanty, S. Nagpure, D.L. Wood, The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling, Carbon N. Y. 105 (2016) 52–76, https://doi.org/10.1016/J.CARBON.2016.04.008.
[154] K. Xu, S.S. Zhang, U. Lee, J.L. Allen, T.R. Jow, LiBOB: is it an alternative salt for lithium ion chemistry? J. Power Sources 146 (1–2) (2005) 79–85, https://doi.org/10.1016/J.JPOWSOUR.2005.03.153.
[155] K. Xu, Tailoring electrolyte composition for LiBOB, J. Electrochem. Soc. 155 (10) (2008) A733, https://doi.org/10.1149/1.2961055/XML.
[156] H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: a review, Energy Convers. Manag. 150 (2017) 304–330, https://doi.org/10.1016/J.ENCONMAN.2017.08.016.
[157] S. Barcellona, L. Codecasa, S. Colnago, L. Piegari, Calendar aging effect on the open circuit voltage of lithium-ion battery, Energies 16 (13) (2023) 4869, https://doi.org/10.3390/EN16134869, 2023*Vol. 16, Page 4869*.
[158] D. Galatro, C. Da Silva, D.A. Romero, O. Trescases, C.H. Amon, Challenges in data-based degradation models for lithium-ion batteries, Int. J. Energy Res. 44 (5) (2020) 3954–3975, https://doi.org/10.1002/ER.5196.
[159] C. Wu, C. Zhu, Y. Ge, Y. Zhao, A review on fault mechanism and diagnosis approach for Li-ion batteries, J. Nanomater. 2015 (2015), https://doi.org/10.1155/2015/631263.
[160] X. Han, et al., A review on the key issues of the lithium ion battery degradation among the whole life cycle, eTransportation 1 (2019) 100005, https://doi.org/10.1016/J.ETRAN.2019.100005.
[161] K. Uddin, S. Perera, W.D. Widanage, L. Somerville, J. Marco, Characterising lithium-ion battery degradation through the identification and tracking of electrochemical battery model parameters, Batter 2 (2) (2016) 13, https://doi.org/10.3390/BATTERIES2020013. *2016, Vol. 2, Page 13*.
[162] B. Xu, A. Oudalov, A. Ulbig, G. Andersson, D.S. Kirschen, Modeling of lithium-ion battery degradation for cell life assessment, IEEE Trans. Smart Grid 9 (2) (2018) 1131–1140, https://doi.org/10.1109/TSG.2016.2578950.
[163] M. Amiri, M. Esfahanian, M.R. Hairi-Yazdi, V. Esfahanian, Minimization of power losses in hybrid electric vehicles in view of the prolonging of battery life, J. Power Sources 190 (2) (2009) 372–379, https://doi.org/10.1016/J.JPOWSOUR.2009.01.072.
[164] A. Millner, Modeling lithium ion battery degradation in electric vehicles, in: 2010 IEEE Conf. Innov. Technol. an Effic. Reliab. Electr. Supply, CITRES 2010, 2010, pp. 349–356, https://doi.org/10.1109/CITRES.2010.5619782.
[165] V. Marano, S. Onori, Y. Guezennec, G. Rizzoni, N. Madella, Lithium-ion batteries life estimation for plug-in hybrid electric vehicles, in: 5th IEEE Veh. Power Propuls. Conf. VPPC '09, 2009, pp. 536–543, https://doi.org/10.1109/VPPC.2009.5289803.

[166] N. Mao, Z.R. Wang, Y.H. Chung, C.M. Shu, Overcharge cycling effect on the thermal behavior, structure, and material of lithium-ion batteries, Appl. Therm. Eng. 163 (2019) 114147, https://doi.org/10.1016/J.APPLTHERMALENG.2019.114147.
[167] B. Lunz, Z. Yan, J.B. Gerschler, D.U. Sauer, Influence of plug-in hybrid electric vehicle charging strategies on charging and battery degradation costs, Energy Policy 46 (2012) 511–519, https://doi.org/10.1016/J.ENPOL.2012.04.017.
[168] T. Waldmann, M. Wilka, M. Kasper, M. Fleischhammer, M. Wohlfahrt-Mehrens, Temperature dependent ageing mechanisms in lithium-ion batteries – A post-mortem study, J. Power Sources 262 (2014) 129–135, https://doi.org/10.1016/J.JPOWSOUR.2014.03.112.
[169] T. Guan, et al., The effect of elevated temperature on the accelerated aging of LiCoO2/mesocarbon microbeads batteries, Appl. Energy 177 (2016) 1–10, https://doi.org/10.1016/J.APENERGY.2016.05.101.
[170] M. Woody, M. Arbabzadeh, G.M. Lewis, G.A. Keoleian, A. Stefanopoulou, Strategies to limit degradation and maximize Li-ion battery service lifetime - Critical review and guidance for stakeholders, J. Energy Storage 28 (2020) 101231, https://doi.org/10.1016/J.EST.2020.101231.
[171] W. Wu, W. Wu, X. Qiu, S. Wang, Low-temperature reversible capacity loss and aging mechanism in lithium-ion batteries for different discharge profiles, Int. J. Energy Res. 43 (1) (2019) 243–253, https://doi.org/10.1002/ER.4257.
[172] M.A. Hannan, M.S.H. Lipu, A. Hussain, A. Mohamed, A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: challenges and recommendations, Renew. Sustain. Energy Rev. 78 (2017) 834–854, https://doi.org/10.1016/J.RSER.2017.05.001.
[173] M. Dubarry, et al., Identifying battery aging mechanisms in large format Li ion cells, J. Power Sources 196 (7) (2011) 3420–3425, https://doi.org/10.1016/J.JPOWSOUR.2010.07.029.
[174] L. Serrao, S. Onori, A. Sciarretta, Y. Guezennec, G. Rizzoni, Optimal energy management of hybrid electric vehicles including battery aging, Proc. Am. Control Conf. (2011) 2125–2130, https://doi.org/10.1109/ACC.2011.5991576.
[175] A. Pesaran, S. Santhanagopalan, and G. Kim, "Addressing the impact of temperature extremes on large format Li-ion batteries for vehicle applications (presentation)," 2013.
[176] K.B. Hatzell, A. Sharma, H.K. Fathy, A survey of long-term health modeling, estimation, and control of lithium-ion batteries: challenges and opportunities, Proc. Am. Control Conf. (2012) 584–591, https://doi.org/10.1109/ACC.2012.6315578.
[177] J. Groot, M. Swierczynski, A.I. Stan, S.K. Kær, On the complex ageing characteristics of high-power LiFePO4/graphite battery cells cycled with high charge and discharge currents, J. Power Sources 286 (2015) 475–487, https://doi.org/10.1016/J.JPOWSOUR.2015.04.001.
[178] G. Ning, B. Haran, B.N. Popov, Capacity fade study of lithium-ion batteries cycled at high discharge rates, J. Power Sources 117 (1–2) (2003) 160–169, https://doi.org/10.1016/S0378-7753(03)00029-6.
[179] A.S. Mussa, et al., Fast-charging effects on ageing for energy-optimized automotive LiNi1/3Mn1/3Co1/3O2/graphite prismatic lithium-ion cells, J. Power Sources 422 (2019) 175–184, https://doi.org/10.1016/J.JPOWSOUR.2019.02.095.
[180] J. Wang, et al., Degradation of lithium ion batteries employing graphite negatives and nickel–cobalt–manganese oxide + spinel manganese oxide positives: part 1, aging mechanisms and life estimation, J. Power Sources 269 (2014) 937–948, https://doi.org/10.1016/J.JPOWSOUR.2014.07.030.
[181] G.H. Kim, A. Pesaran, R. Spotnitz, A three-dimensional thermal abuse model for lithium-ion cells, J. Power Sources 170 (2) (2007) 476–489, https://doi.org/10.1016/J.JPOWSOUR.2007.04.018.
[182] J. Xu, C. Lan, Y. Qiao, Y. Ma, Prevent thermal runaway of lithium-ion batteries with minichannel cooling, Appl. Therm. Eng. 110 (2017) 883–890, https://doi.org/10.1016/J.APPLTHERMALENG.2016.08.151.
[183] M. Xu, Z. Zhang, X. Wang, L. Jia, L. Yang, A pseudo three-dimensional electrochemical e thermal model of a prismatic LiFePO 4 battery during discharge process, Energy (2014), https://doi.org/10.1016/j.energy.2014.11.073.
[184] M. Xu, Z. Zhang, X. Wang, L. Jia, L. Yang, Two-dimensional electrochemical e thermal coupled modeling of cylindrical LiFePO 4 batteries, J. Power Sources 256 (2014) 233–243, https://doi.org/10.1016/j.jpowsour.2014.01.070.
[185] H. Li, et al., Electrochemical and thermal characteristics of prismatic lithium-ion battery based on a three-dimensional electrochemical-thermal coupled model, J. Energy Storage 42 (August) (2021) 102976, https://doi.org/10.1016/j.est.2021.102976.
[186] X. Lin, et al., Non-uniform thermal characteristics investigation of three-dimensional electrochemical-thermal coupled model for pouch lithium-ion battery, J. Clean. Prod. 417 (June) (2023) 137912, https://doi.org/10.1016/j.jclepro.2023.137912.
[187] S. Basu, R.S. Patil, S. Ramachandran, K.S. Hariharan, Non-isothermal electrochemical model for lithium-ion cells with composite cathodes, J. Power Sources 283 (2015) 132–150, https://doi.org/10.1016/j.jpowsour.2015.02.127.
[188] S. Chavan, et al., Thermal runaway and mitigation strategies for electric vehicle lithium-ion batteries using battery cooling approach: a review of the current status and challenges, J. Energy Storage 72 (July) (2023), https://doi.org/10.1016/j.est.2023.108569.
[189] G. Saldana, J.I.S. Martin, I. Zamora, F.J. Asensio, O. Onederra, M. Gonzalez, Empirical electrical and degradation model for electric vehicle batteries, IEEE Access 8 (2020) 155576–155589, https://doi.org/10.1109/ACCESS.2020.3019477.
[190] N.F. F, E.R. Carlson, Monotone piecewise cubic interpolation, SIAM J. Numer. Anal. 17 (2) (1980) 238–246, https://doi.org/10.1137/0717021.
[191] F.J. Asensio, J.I. San Martín, I. Zamora, O. Oñederra, Model for optimal management of the cooling system of a fuel cell-based combined heat and power system for developing optimization control strategies, Appl. Energy 211 (2018) 413–430, https://doi.org/10.1016/J.APENERGY.2017.11.066.
[192] C. Roe, et al., Immersion cooling for lithium-ion batteries – A review, J. Power Sources 525 (August 2021) (2022) 231094, https://doi.org/10.1016/j.jpowsour.2022.231094.
[193] X. Zhang, X. Fan, Y. Deng, Cooling performance optimization of air-cooled battery thermal management system with L-type flow, Energy Technol. 11 (9) (2023) 2300382, https://doi.org/10.1002/ENTE.202300382.
[194] X. Zhu, X. Xu, B. Kong, J. Wang, H. Shi, Y. Jiang, Coupling simulation of the cooling air duct and the battery pack in battery energy storage systems, Phys. Scr. 98 (7) (2023) 075906, https://doi.org/10.1088/1402-4896/ACD824.
[195] Z. Feng, et al., Optimization of the cooling performance of symmetric battery thermal management systems at high discharge rates, Energy Fuels 37 (11) (2023) 7990–8004, https://doi.org/10.1021/ACS.ENERGYFUELS.3C00690/SUPPL_FILE/EF3C00690_SI_001.PDF.
[196] D. Zhang, X. Zhao, M. Zhang, H. Yang, S. Li, T. Zhou, Research on air-cooled thermal management of energy storage lithium battery, Asia-Pacific J. Chem. Eng. 18 (4) (2023) e2924, https://doi.org/10.1002/APJ.2924.
[197] T. Hai, A. Abidi, S.M. Sajadi, J.M. Zain, E.H. Malekshah, H. Aybar, Simultaneous cooling of plate and cylindrical batteries in an air-cooled lithium battery thermal management system, by changing the distances of the batteries from each other and the pack wall, J. Taiwan Inst. Chem. Eng. 148 (2023) 104931, https://doi.org/10.1016/J.JTICE.2023.104931.
[198] O.M. Oyewola, A.A. Awonusi, O.S. Ismail, Design optimization of air-cooled Li-ion battery thermal management system with step-like divergence plenum for electric vehicles, Alexandria Eng. J. 71 (2023) 631–644, https://doi.org/10.1016/j.aej.2023.03.089.
[199] C. Yang, H. Xi, M. Wang, Structure optimization of air cooling battery thermal management system based on lithium-ion battery, J. Energy Storage 59 (2023) 106538, https://doi.org/10.1016/J.EST.2022.106538.
[200] C. Wang, J. Xu, M. Wang, H. Xi, Experimental investigation on reciprocating air-cooling strategy of battery thermal management system, J. Energy Storage 58 (2023) 106406, https://doi.org/10.1016/J.EST.2022.106406.
[201] X. Zhang, X. Fan, Performance optimization of air cooling battery thermal management system based on structure design, in: 2022 5th Int. Conf. Renew. Energy Power Eng. REPE 2022, 2022, pp. 437–441, https://doi.org/10.1109/REPE55559.2022.9949345.
[202] W. Chen, et al., Numerical analysis of novel air-based Li-ion battery thermal management, Batter 8 (9) (2022) 128, https://doi.org/10.3390/BATTERIES8090128. *2022, Vol. 8, Page 128*.
[203] G. Zhao, X. Wang, M. Negnevitsky, H. Zhang, A design optimization study of an air-cooling battery thermal management system for electric vehicles, Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng. 237 (4) (2023) 1125–1136, https://doi.org/10.1177/09544089221116418/ASSET/IMAGES/LARGE/10.1177_09544089221116418-FIG10.JPEG.
[204] O.M. Oyewola, A.A. Awonusi, O.S. Ismail, Performance improvement of air-cooled battery thermal management system using sink of different pin-fin shapes, Emerg. Sci. J. 6 (4) (2022) 851–865, https://doi.org/10.28991/ESJ-2022-06-04-013.
[205] K. Ding, Z. Lin, B. Xie, Thermal management design and simulation of symmetric air-cooled system for lithium battery, SAE Tech. Pap. (2023), https://doi.org/10.4271/2023-01-0517.
[206] A.R. Mundonkakkoth, N. Menon, T.K. Raj, Design and analysis of liquid-cooled battery thermal management system of electric vehicles, Lect. Notes Mech. Eng. (2023) 299–312, https://doi.org/10.1007/978-981-19-6032-1_24/COVER.
[207] S. Sunkara and S. Hayath, "Indian journal of software engineering and project management (IJSEPM) battery thermal management system for electric vehicles", doi: 10.54105/ijsepm.A9017.013123.
[208] B. Chidambaranathan, et al., Thermal management system in electric vehicle batteries for environmental sustainability, Environ. Qual. Manag. 33 (2) (2023) 159–167, https://doi.org/10.1002/TQEM.22001.
[209] R.A. Pires, S.A. Carvalho, B.J. Cardoso Filho, I.A. Pires, R. Huebner, T.A.C. Maia, The assessment of electric vehicle storage lifetime using battery thermal management system, Batter 9 (1) (2022) 10, https://doi.org/10.3390/BATTERIES9010010, 2023*Vol. 9, Page 10*.
[210] Z. Guo, Y. Wang, S. Zhao, T. Zhao, M. Ni, Modeling and optimization of liquid-based battery thermal management system considering battery electrochemical characteristics, J. Energy Storage 70 (2023) 108028, https://doi.org/10.1016/J.EST.2023.108028.
[211] T. Ebbs-Picken, C.M. Da Silva, C.H. Amon, Design optimization methodologies applied to battery thermal management systems: a review, J. Energy Storage 67 (2023) 107460, https://doi.org/10.1016/J.EST.2023.107460.
[212] L. Cattani, M. Malavasi, F. Bozzoli, V. D'Alessandro, L. Giammichele, Experimental analysis of an innovative electrical battery thermal management system, Energies 16 (13) (2023) 5071, https://doi.org/10.3390/EN16135071, 2023*Vol. 16, Page 5071*.
[213] G. Zhao, X. Wang, M. Negnevitsky, H. Zhang, A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles, J. Power Sources 501 (April) (2021) 230001, https://doi.org/10.1016/j.jpowsour.2021.230001.
[214] M. Akbarzadeh, et al., A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module, Appl. Therm. Eng. 198 (August) (2021) 117503, https://doi.org/10.1016/j.applthermaleng.2021.117503.

[215] R. Pakrouh, M.J. Hosseini, A.A. Ranjbar, M. Rahimi, A novel liquid-based battery thermal management system coupling with phase change material and thermoelectric cooling, J. Energy Storage 64 (2023) 107098, https://doi.org/10.1016/J.EST.2023.107098.
[216] R. Fan, C. Wang, H. Xi, Propose and experimental validation of a light-weight and shock-proof liquid cooling battery thermal management system, J. Energy Storage 62 (2023) 106933, https://doi.org/10.1016/J.EST.2023.106933.
[217] D. Karimi, R. Behi, M. Behnia, A. Kumar, Identification and mitigation of shortcomings in direct and indirect liquid cooling-based battery thermal management system, Energies 16 (9) (2023) 3857, https://doi.org/10.3390/EN16093857, 2023*Vol. 16, Page 3857*.
[218] W. Zhong, M. Li, W. Shangguan, Structural design and optimization of liquid-cooled thermal management components for electric vehicle batteries, SAE Tech. Pap. (2023), https://doi.org/10.4271/2023-01-0768.
[219] H. Yang, Z. Wang, M. Li, F. Ren, B. Ma, Numerical study on cross-linked cold plate design for thermal management of high-power lithium-ion battery, Batteries 9 (4) (2023), https://doi.org/10.3390/batteries9040220.
[220] G.A. KILIC, An experimental analysis on the effects of passive liquid cooling system on thermal management system, Int. J. Thermofluids 18 (2023) 100370, https://doi.org/10.1016/J.IJFT.2023.100370.
[221] S. Durgam, V.M. Deshmukh, Thermal management of lithium-ion battery pack with liquid cooling: a computational investigation, Lect. Notes Mech. Eng. (2023) 357–370, https://doi.org/10.1007/978-981-19-7214-0_30/COVER.
[222] J. Zeng, et al., Numerical analysis on thermal management performance of lithium-ion battery pack with liquid cooling, Lect. Notes Electr. Eng. 1016 LNEE (2023) 809–823, https://doi.org/10.1007/978-981-99-1027-4_84/COVER.
[223] J. Xiao, H. Zhang, S. Kelouwani, T. Brezesinski, R. Lloyd, M. Akrami, A critical analysis of helical and linear channel liquid cooling designs for lithium-ion battery packs, Batter 8 (11) (2022) 236, https://doi.org/10.3390/BATTERIES8110236. *2022, Vol. 8, Page 236*.
[224] D. Wang, J. Xie, D. Wang, J. Xie, Investigation of the liquid cooling and heating of a lithium-ion battery package for an electric vehicle, World Electr. Veh. J. 14 (7) (2023) 169, https://doi.org/10.3390/WEVJ14070169, 2023*Vol. 14, Page 169*.
[225] M. Yates, M. Akrami, A.A. Javadi, Analysing the performance of liquid cooling designs in cylindrical lithium-ion batteries, J. Energy Storage 33 (2021) 100913, https://doi.org/10.1016/j.est.2019.100913.
[226] Y. Ding, M. Wei, R. Liu, Parameters of liquid cooling thermal management system effect on the Li-ion battery temperature distribution, Therm. Sci. 26 (1) (2022) 567–577, https://doi.org/10.2298/TSCI201019223D. Part B.
[227] W. Wu, S. Wang, W. Wu, K. Chen, S. Hong, Y. Lai, A critical review of battery thermal performance and liquid based battery thermal management, Energy Convers. Manag. 182 (December 2018) (2019) 262–281, https://doi.org/10.1016/j.enconman.2018.12.051.
[228] P.R. Tete, M.M. Gupta, S.S. Joshi, Developments in battery thermal management systems for electric vehicles : a technical review state of power, J. Energy Storage 35 (September 2020) (2021) 102255, https://doi.org/10.1016/j.est.2021.102255.
[229] Q. Liu, Q. Deng, R. Zhao, W.L. Cheng, Y.D. Wang, A novel flexible flame-retardant phase change materials with battery thermal management test, J. Energy Storage 70 (2023) 108077, https://doi.org/10.1016/J.EST.2023.108077.
[230] S. Ahmad, Y. Liu, S.A. Khan, M. Hao, X. Huang, Hybrid battery thermal management by coupling fin intensified phase change material with air cooling, J. Energy Storage 64 (2023) 107167, https://doi.org/10.1016/J.EST.2023.107167.
[231] Y.A. Bhutto, A.K. Pandey, R. Saidur, K. Sharma, V.V. Tyagi, Critical insights and recent updates on passive battery thermal management system integrated with nano-enhanced phase change materials, Mater. Today Sustain. 23 (2023) 100443, https://doi.org/10.1016/J.MTSUST.2023.100443.
[232] Z. Yu, J. Zhang, W. Pan, A review of battery thermal management systems about heat pipe and phase change materials, J. Energy Storage 62 (2023), https://doi.org/10.1016/J.EST.2023.106827.
[233] C. Liu, et al., Phase change materials application in battery thermal management system: a review, Mater. 13 (20) (2020) 4622, https://doi.org/10.3390/MA13204622, 2020*Vol. 13, Page 4622*.
[234] J. Lu et al., "Battery degradation prediction against uncertain future conditions with recurrent neural network enabled deep learning," vol. 50, no. April, pp. 139–151, 2022, doi: 10.1016/j.ensm.2022.05.007.
[235] Z. Yu, J. Zhang, W. Pan, A review of battery thermal management systems about heat pipe and phase change materials, J. Energy Storage 62 (2023) 106827, https://doi.org/10.1016/J.EST.2023.106827.
[236] A. Afzal, R.K. Abdul Razak, A.D. Mohammed Samee, R. Kumar, Ü. Ağbulut, S. G. Park, A critical review on renewable battery thermal management system using heat pipes, J. Therm. Anal. Calorim. 148 (16) (2023) 8403–8442, https://doi.org/10.1007/S10973-023-12100-9/TABLES/6.
[237] Y. Xu, Z. Wang, Z. Ke, B. Lai, Y. Zhang, X. Huang, Experimental and simulation research on heat pipe thermal management system coupled with battery thermo-electric model, Process 11 (4) (2023) 1204, https://doi.org/10.3390/PR11041204, 2023*Vol. 11, Page 1204*.
[238] P. Li, Q. Zeng, M. Ma, Y. Zhang, Z. Ke, W. Wu, Numerical study of the performance of heat pipe-based thermal management system for power lithium battery, Heat Transf. Res. 54 (14) (2023) 63–77, https://doi.org/10.1615/HEATTRANSRES.2023047361.
[239] W.N. Septiadi, M. Alim, M.N.P. Adi, The application of battery thermal management system based on heat pipes and phase change materials in the electric bike, J. Energy Storage 56 (2022) 106014, https://doi.org/10.1016/J.EST.2022.106014.
[240] K. Boonma, et al., A review of the parameters affecting a heat pipe thermal management system for lithium-ion batteries, Energies 15 (22) (2022) 8534, https://doi.org/10.3390/EN15228534, 2022*Vol. 15, Page 8534*.
[241] P.S. Shinde, P. Naik, Heat-pipe-assisted air cooling of lithium-titanate prismatic battery, J. Therm. Sci. Eng. Appl. 15 (2) (2023), https://doi.org/10.1115/1.4056241.
[242] E. Guinan, J. Mooney, J. Ottman, J. Punch, and V. Egan, "Analysis of a battery thermal management system for electric vehicles using heat pipe technology," 2022, doi: 10.11159/htff22.161.
[243] B. Ariantara, N. Putra, S. Supriadi, Battery thermal management system using loop heat pipe with LTP copper capillary wick, IOP Conf. Ser. Earth Environ. Sci. 105 (1) (2018) 012045, https://doi.org/10.1088/1755-1315/105/1/012045.
[244] X. Ye, Y. Zhao, Z. Quan, Thermal management system of lithium-ion battery module based on micro heat pipe array, Int. J. Energy Res. 42 (2) (2018) 648–655, https://doi.org/10.1002/er.3847.
[245] R. Wrobel, R.J. McGlen, Heat pipes in thermal management of electrical machines – A review, Therm. Sci. Eng. Prog. 26 (2021) 101053, https://doi.org/10.1016/J.TSEP.2021.101053.
[246] R.R. Riehl, J.E.S. Martin, J. Estella, Electronics thermal management applying heat pipes and pulsating heat pipes, Adv. Nanofluid Heat Transf. (2022) 403–446, https://doi.org/10.1016/B978-0-323-88656-7.00001-5.
[247] D.M. Weragoda, G. Tian, A. Burkitbayev, K. Lo, T. Zhang, A comprehensive review on heat pipe based battery thermal management systems, Appl. Therm. Eng. 224 (January) (2023) 120070, https://doi.org/10.1016/j.applthermaleng.2023.120070.
[248] Y. Xie, et al., Improving thermal performance of battery at high current rate by using embedded heat pipe system, J. Energy Storage 46 (November 2021) (2022), https://doi.org/10.1016/j.est.2021.103809.
[249] Y.S. Ranjbaran, M.H. Shojaeefard, G.R. Molaeimanesh, Thermal performance enhancement of a passive battery thermal management system based on phase change material using cold air passageways for lithium batteries, J. Energy Storage 68 (2023) 107744, https://doi.org/10.1016/J.EST.2023.107744.
[250] R. Aryal, A. Anand, N.K. Saxena, P. Vaidianathan, M.B. Shyamkumar, Thermal management of automobile batteries using hybrid cooling - A review, IOP Conf. Ser. Earth Environ. Sci. 1161 (1) (2023) 012014, https://doi.org/10.1088/1755-1315/1161/1/012014.
[251] B. Shu, M. Skyllas-Kazacos, J. Bao, K. Meng, Hybrid cooling-based thermal management of containerised vanadium flow battery systems in photovoltaic applications, Processes 11 (5) (2023) 1431, https://doi.org/10.3390/PR11051431, 2023*Vol. 11, Page 1431*.
[252] R.M. Raja Ahsan Shah, M. Al Qubeissi, H. Youssef, H.S. Soyhan, Battery thermal management: an application to petrol hybrid electric vehicles, Sustainability 15 (7) (2023) 5868, https://doi.org/10.3390/SU15075868, 2023*Vol. 15, Page 5868*.
[253] K.A. Swamy, S. Verma, L. Mittal, Numerical investigation on optimisation of the mass of PCM in a hybrid battery thermal management system, Lect. Notes Mech. Eng. (2023) 443–448, https://doi.org/10.1007/978-981-19-6270-7_74/COVER.
[254] S. Jin, Q. Gao, T. Zhang, Simulation of battery simultaneous cooling based on the dual fluid medium system, J. Energy Storage 61 (2023) 106732, https://doi.org/10.1016/J.EST.2023.106732.
[255] J. Kittleson, A. Mukherjee, Numerical investigation on the suitability of a PCM/refrigerant hybrid cooling system for lithium-ion batteries, ASME Int. Mech. Eng. Congr. Expo. Proc. 8 (2023), https://doi.org/10.1115/IMECE2022-96031.
[256] J. Weng, et al., An energy-saving battery thermal management strategy coupling tubular phase-change-material with dynamic liquid cooling under different ambient temperatures, Renew. Energy 195 (2022) 918–930, https://doi.org/10.1016/j.renene.2022.06.025.
[257] K.R. Patil, A.K. Raul, A. Anbhule, M. Barve, A. Bedare, Y. Magare, Performance evaluation of BTMS for electric vehicles using heat sink - a numerical study, Int. J. Veh. Struct. Syst. 15 (1) (2023) 37–45, https://doi.org/10.4273/IJVSS.15.1.07.
[258] A.A. Alnaqi, Numerical analysis of pressure drop and heat transfer of a non-Newtonian nanofluids in a Li-ion battery thermal management system (BTMS) using bionic geometries, J. Energy Storage 45 (2022) 103670, https://doi.org/10.1016/J.EST.2021.103670.
[259] M. Piasecka, K. Dutkowski, Novel numerical methods in heat and mass transfer, Energies 15 (7) (2022) 2635, https://doi.org/10.3390/EN15072635, 2022*Vol. 15, Page 2635*.
[260] K. Yeranee, Y.A. Rao, K. Yeranee, Y. Rao, A review of recent investigations on flow and heat transfer enhancement in cooling channels embedded with triply periodic minimal surfaces (TPMS), Energies 15 (23) (2022) 8994, https://doi.org/10.3390/EN15238994, 2022*Vol. 15, Page 8994*.
[261] D. Taylor, L. Fasciati, T. Roy, D. Poulikakos, Experimental analysis of heat transfer to shear-thinning viscoelastic coolants for optimizing surface topographies in immersed battery cooling systems, Intersoc. Conf. Therm. Thermomechanical Phenom. Electron. Syst. ITHERM 2022-May (2022), https://doi.org/10.1109/ITHERM54085.2022.9899669.
[262] H. Yasmin, S.O. Giwa, S. Noor, M. Sharifpur, Applicability of hybrid nanofluids as energy-efficient coolants in heat transfer systems: an experimental overview, Nanofluid Appl. Adv. Therm. Solut. (2023) 63–115, https://doi.org/10.1016/B978-0-443-15239-9.00004-7.
[263] S.M. Sohel Murshed, C.A. Nieto de Castro, A critical review of traditional and emerging techniques and fluids for electronics cooling, Renew. Sustain. Energy Rev. 78 (2017) 821–833, https://doi.org/10.1016/J.RSER.2017.04.112.
[264] K.R. Aglawe, R.K. Yadav, S.B. Thool, Current technologies on electronics cooling and scope for further improvement: a typical review, Lect. Notes Multidiscip. Ind.

Eng. Part F41 (2022) 389–408, https://doi.org/10.1007/978-3-030-73495-4_27/COVER.

[265] R.D. Pathumudy, K.N. Prabhu, Thermal interface materials for cooling microelectronic systems: present status and future challenges, J. Mater. Sci. Mater. Electron. 32 (9) (2021) 11339–11366, https://doi.org/10.1007/S10854-021-05635-W. *2021 329*.

[266] W. Li, A.K. Jishnu, A. Garg, M. Xiao, X. Peng, L. Gao, Heat transfer efficiency enhancement of lithium-ion battery packs by using novel design of herringbone fins, Nutr. Today 17 (2) (2020), https://doi.org/10.1115/1.4046160/1073991.