

Challenges and opportunities toward fast-charging of lithium-ion batteries

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ABSTRACT

Improving the rate capability of lithium-ion batteries is beneficial to the convenience of electric vehicle application. The high-rate charging, however, leads to lithium inventory loss, mechanical effects and even thermal runaway. Therefore, the optimal charging algorithm of Li-ion batteries should achieve the shortest charging interval with minimal degradation. This paper thoroughly reviews the recent progress on fast charging in terms of material chemistry, thermal issues and charging optimization. Specifically, the microscale mechanisms that limit rate capability are explored and methods for material modification are addressed in detail. To improve the operation safety and battery lifespan at wider temperature ranges, side reactions induced by charging at extreme temperatures are analyzed and solutions are discussed. Preheating at low temperatures is highlighted especially. Furthermore, charging optimization based on local volume expansion, battery model and big data is summarized. Finally, challenges and promising directions as possible inspirations for future research towards fast charging are proposed.

1. Introduction

Lithium-ion (Li-ion) batteries exhibit advantages of high power density, high energy density, comparatively long lifespan and environmental friendliness, thus playing a decisive role in the development of consumer electronics and electric vehicles (EVs) [1–3]. Although tremendous progress of Li-ion batteries has been made, range anxiety and time-consuming charging pose technical obstacles to the widespread of EVs [4]. While increased pack capacity of battery enables long driving range, the corresponding increase in charging time counteracts the customer's expectations. Shortening the charging time without sacrificing driving range can greatly improve convenience of customers. Fast charging has become the long-term strategic target for the development of power batteries in EV industries [5].

Unfortunately, there is no uniform definition regarding fast charging until now. The goal of U.S. Advanced Battery Consortium for fast charging is to refill 40% state of charge (SOC), starting from approximately 60% depth of discharge within 15 mins [6]. The Ministry of Industry and Information Technology of China has stipulated the certification requirement for fast charging of mobile telecommunication terminal equipment; that is, recharge to 60% of the battery capacity

from the initial charging state within 30 mins charging [7]. In recent years, the automotive industry widely accepted the target of charging a fully discharged battery to 80% SOC within 15 min [8]. Furthermore, the US Department of Energy has proposed the target of extreme fast charging (XFC; $\geq 6C$) technology, which adds 200 miles range within 10 mins charging. Unfortunately, limited by the tolerance of material chemistry, it is difficult to fully charge the battery in a few minutes [9]. Meanwhile, various definitions of fast charging might induce misinterpretation and hinder the further progress of charging technology with the extended application scenario and functionality. Nevertheless, the long-term goal of charging technology for EV must be as fast as refueling an internal-combustion vehicle. In order to achieve convenience comparable to the refueling, the industry has taken measures to increase the charging power up to 400 kW [5]. As a matter of fact, the improved power capability of EV chargers does not indicate that fast charging can be implemented in EVs. On the other hand, the endurance of the battery under high current or high voltage is a key rate capability limiting factor [9,10]. Numerous studies have demonstrated that the critical challenge for fast charging lies in battery rather than charger [5]. Increasing charging current shortens charging time but accelerates the battery degradation simultaneously. Typically, charging

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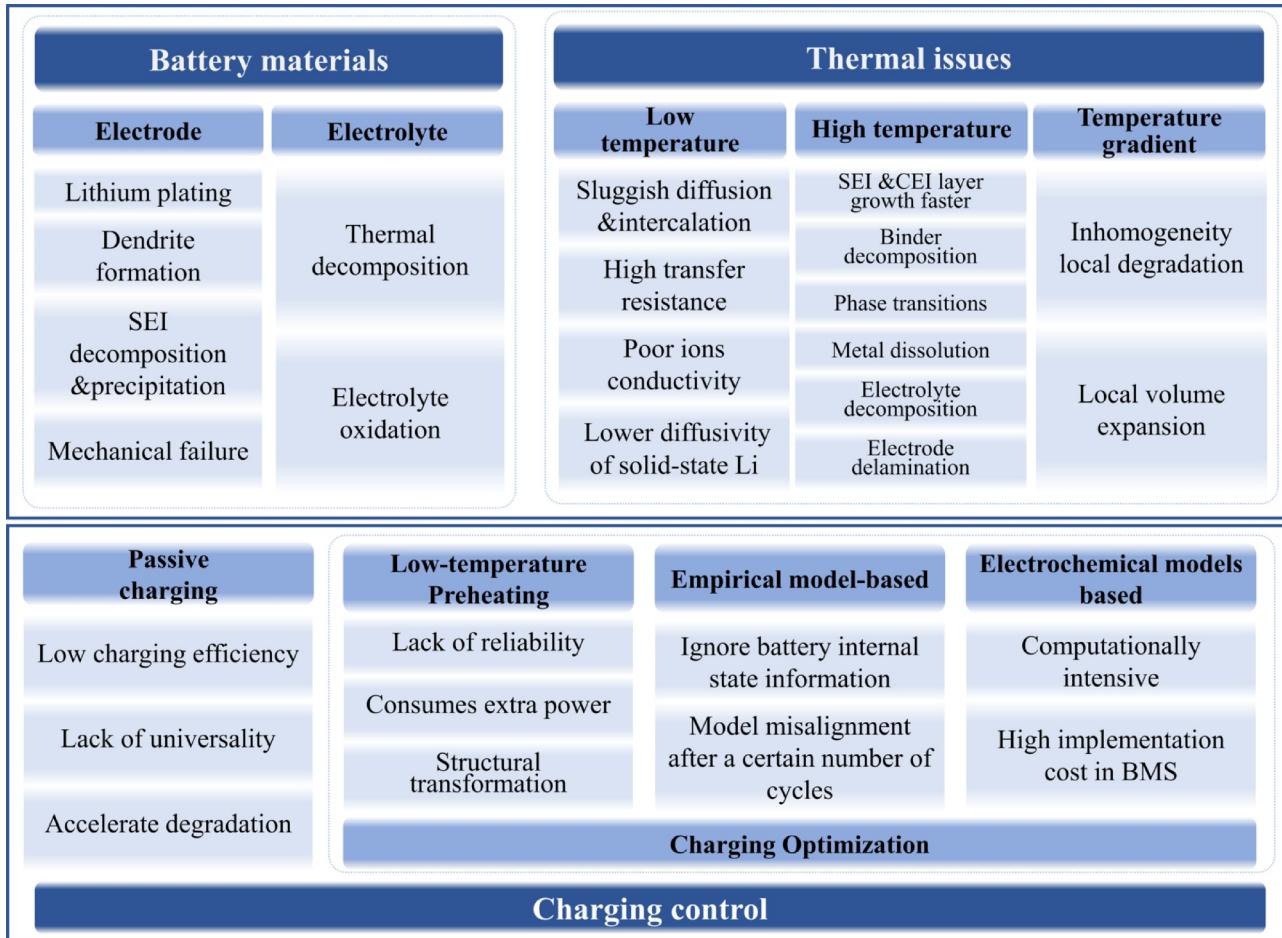


Fig. 1. Multiple challenges for fast charging of lithium ion batteries. (TIFF format, 762 dpi*762 dpi, 2-column fitting image).

rate has more significant effect on battery degradation than discharge rate. Although some Li-ion batteries with high power density are optimized for 10C discharge, the maximum charging rate of most commercial Li-ion batteries are limited to 3C [5,11].

High rate charging induced side reactions, such as lithium plating, mechanical effects and heat generation, which will accelerate the battery degradation [12,13]. For cold areas at high latitudes, low temperatures limit the charging rate severely ascribe to the lower diffusion coefficient in liquid phase and sluggish interfacial kinetics in solid phase [14]. On the other hand, the heat generation in charging will accelerate the side reaction rate and eventually result in safety problems without prompt and homogeneous dissipation [15].

In brief, the implementation of fast charging should not only shorten the charging time, but also restrain the degradation as much as possible [16]. Fig. 1 summarized the multiple challenges for fast charging of lithium ion batteries. For example, the potential degradation of material caused by fast charging, mechanisms limiting charging efficiency at low temperatures. The adverse effects of temperature rise induced by fast charging and intensified temperature gradient on battery performance. From the perspective of charging control, charging protocols can be divided into passive charging and optimized charging according to whether the charging profile changes actively with the internal states of the battery [17]. Passive charging is easy to implement but cannot achieve optimal charging [18], and the reliability of low temperature preheating still needs to be further verified. Finally, the model-based optimization needs to achieve the optimal balance between high simulation accuracy and model simplification for online application. This paper summarizes the degradation mechanism of batteries induced by fast charging and exhibits the multidisciplinary nature of charging

technology. Recent research progress is reviewed from the perspective of material properties, electrochemistry, thermodynamics and charging optimization algorithm. In addition, the potential for charging performance improvement is highlighted. Finally, the promising research hotspots toward fast charging are prospected.

2. The requirements on materials for Li-ion battery fast charging

Electrodes with high porosity or low tortuosity and electrolytes with excellent ionic conductivity are more conducive to fast charging [19,20]. Charging with high rates tends to accelerate degradation of Li-ion battery ascribe to the inhomogeneous current density, temperature distribution at the macroscale as well as the restricted diffusion kinetics of Li^+ at the microscale [21]. The rate capability depends on the migration and diffusion of ions in the electrodes, electrolytes and their interfaces [22,23]. Clarifying the restriction mechanism of Li^+ transfer and diffusion kinetics is critical for the improvement of rate capability, especially at subzero temperatures [24]. In addition, the main challenge of XFC shifts from reaction-limited to the transport-limited regime. In particular, the mass transfer limitations will amplify underlying heterogeneities and electrode inhomogeneities contribute to nonuniform plating. Therefore, the exploration of complex interactions induced by the rapid dynamics of inhomogeneous electrodes is a prerequisite towards XFC [25].

Essentially, electrode materials exhibit more significant restrictions on rate capability than electrolytes at moderate temperature [20]. Meanwhile, the anode draws more attention than cathode towards fast charging [23,26]. Mao et al. [27] adopted both symmetric and half cells of NMC811/graphite to investigate the rate capability of the cathode

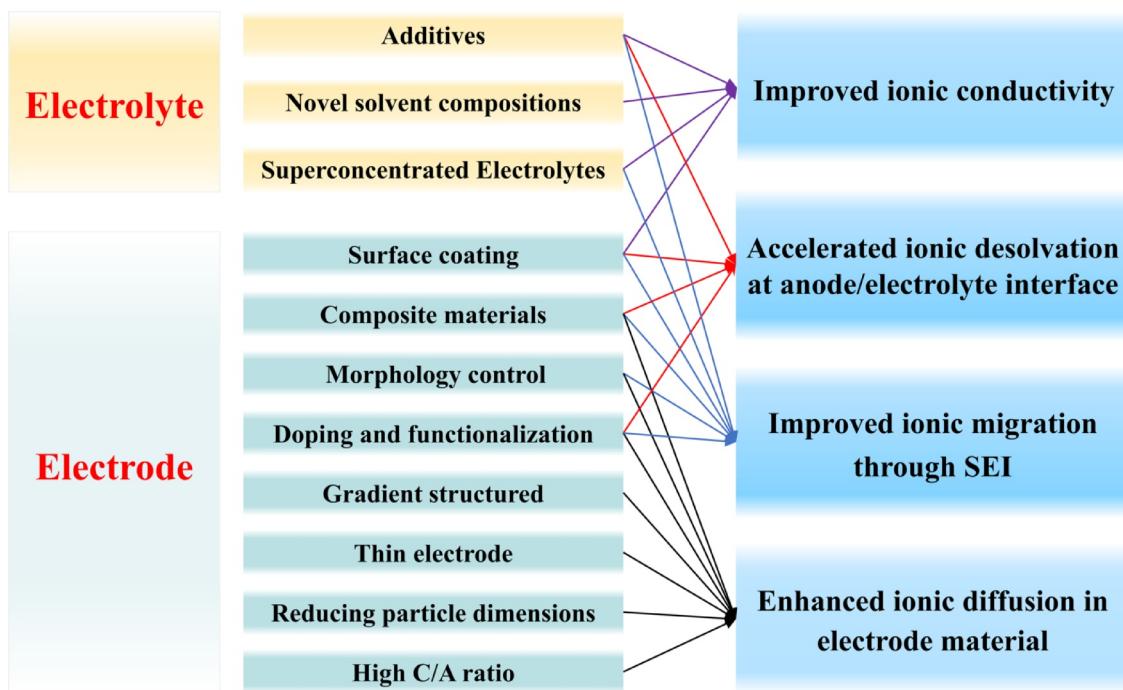


Fig. 2. General strategies for rate capability enhancement at the material level. (TIFF format, 762 dpi*762 dpi, 1.5-column fitting image).

and anode separately, the results revealed that the graphite anode exhibits significant capacity fade at high C-rates. Although the cathode degradation accelerates battery aging, it was not the critical challenge of fast charging [28]. In addition, increasing the porosity of separator or decreasing the thickness of separator has a slight effect on improving rate capability [29,30].

Strategies including electrode surface modification, interface morphology control, composite material development, electrolyte additive application, optimization of electrode macro dimension can improve the conductivity of lithium ions, accelerate interface desolvation and migration through SEI and enhance ionic diffusion in electrode material. Fig. 2 summarized the general strategy for improving the rate capability from the perspective of electrodes and electrolytes.

Electrolyte characteristics are essential to the rate capability of Li-ion batteries. Modification strategies include the application of electrolyte additives, the development of novel solvent compositions and supreconcentrated electrolytes. The improvement of rate performance is mainly attributed to the higher electrolyte conductivity and enhanced interface dynamics.

Improvement strategies for electrode include surface coating, application of composite materials, morphology control, doping and functionalization, gradient structured and macro-level design. Surface coating synthesizes the electrode by chemical deposition and forms a protective interfacial layer to construct the core-shell structure. The protective interfacial layer can inhibit the side reactions such as graphite stripping, active material pulverization and improve the compatibility between electrode materials and electrolyte, which contributes to the good stability at high C-rates. Composite materials have shown great potential in the development of Li-ion batteries with excellent rate capability. Benefiting from the high conductivity, increased porosity and Li^+ ions diffusion coefficients, composite materials with alternative compositions have attracted extensive attention. The strategy of morphology control can improve the porosity or reduce the tortuosity of electrode materials by chemical or physical methods, which accelerates the transport of lithium ions and enhances the interfacial stability. The electrode doping strategy optimizes its microstructure and charge state by selectively doping certain chemical elements, which enhances the lithium ion intercalation/deintercalation

kinetics. The modification of electrode materials from the perspective of physics is also critical to achieving health-conscious fast charging. Smaller particles are more resilient to the mechanical effects and lithium concentration gradients induced by fast charging, but deteriorate the energy density of battery. Therefore, it is necessary to evaluate the critical size of electrode particles that can make a trade-off between energy density and rate capability. Similarly, the optimal areal capacity ratio of cathode to anode (C/A) should be able to inhibit lithium deposition and avoid cathode overcharging.

2.1. Challenges for electrodes

2.1.1. Improvement in anode

Currently, materials used for the anode of commercial Li-ion battery are carbon-based alternatives (graphite, carbon nanotubes, graphene or graphene oxide), LTO (lithium titanate oxide) [31–33]. Graphite is the most widely accepted anode material due to its excellent reversibility, low cost and safety [20,34]. Numerous researches have demonstrated that the growth of solid electrolyte interface (SEI) layer consumes electrolyte and lithium inventory, which is harmful to the formation of stable interface structure [37,38]. Although the growth of SEI layer is not the critical side reaction induced by fast charging, continuous thickening of the passive layer may clog the electrode pores and induce an impedance rise [36,39]. In particular, the equilibrium potential of graphite anode is fairly close to the reversible potential of lithium deposition/dissolution and can drop below 0 V vs Li/Li^+ under extreme charging operations such as high C-rates or low temperatures [36,40]. Lithium ions are reduced to metallic lithium at the anode/electrolyte interfaces instead of intercalating into the particle lattice, which results in lithium plating and significantly deteriorates the lifespan and safety of batteries. Lithium plating not only results in accelerated capacity loss [41], but also detrimental to safety [42]. More specifically, lithium plating clogs the porosity of active materials and accelerates the loss of lithium inventory (LLI) and electrolyte decomposition [43]. It should be noted that the decrease of active surface area increases the anode interfacial overpotential, therefore, metallic lithium is preferentially deposited in the existing deposits. Meanwhile, the enhanced local current density on lithium deposition increases localized high temperature

which further accelerates Li deposition rates [44]. In addition, exothermic reactions of the plated metallic lithium and surrounding electrolyte leads to the drastic heat generation accompanied with the venting of gaseous electrolyte decomposition products [42]. On the other hand, the existence of plated lithium tends to decrease the initial temperature of thermal runaway [42,45–47]. Even worse, the formation of lithium dendrites pose the risk of separator puncture and lead to internal micro-short circuits [52].

In brief, lithium plating induced by fast charging significantly deteriorates the battery performance and safety, which is considered as the major challenge towards fast charging. The rest periods after high current cyclic aging tests have been proved to be effective to mitigate the battery degradation, which should be ascribed to the reactivation of passivated metallic lithium plating [48,49]. Waldmann et al. [48] investigated the effects of rest time on safety behavior of lithium ion battery after Li plating. The accelerated rate calorimetry (ARC) test revealed that the longer rest of Li plating cells takes more time than the shorter rest cells until thermal runaway, and both are less than the time required for fresh cells. This indicates that the chemical re-intercalation of metallic Li into graphite during the rest time reduces the lithium plating. Correspondingly, the re-intercalation of reversibly plated lithium into the anode reduces the capacity loss. In addition, the microcurrent discharge is also conducive to eliminating the lithium deposits [50]. However, the above two strategies cannot be applied to the real-time application of battery management system (BMS) [51]. Therefore, the real-time quantitative observation of the amount of plated lithium and chemical reintercalation of plated lithium metal is a promising electro-chemical technology such as the in-situ methods, voltage relaxation profile analysis and electrochemical model [52–55], which provides the possibility to reduce the amount of lithium plating and further charging optimization [50,56–58].

In order to restrain side reactions such as lithium plating on the anode/electrolyte interface, the rate of charge transfer from cathode to anode should be enhanced at high C-rates [35,59]. Specifically, the Li⁺ charge transfer at a graphite anode can be divided into the following processes: 1) Li⁺ desolvation at the anode/electrolyte interface; 2) migration of the Li⁺ through SEI layer; 3) diffusion of solid-state Li in carbon galleries of anode particles. Meanwhile, electrons are transferred from the cathode to anode through external circuit, and finally merge with Li⁺ on the anode. The improvement of above processes is essential towards fast charging [20].

Table 1 summarized the typical strategies for improving rate

capability in anode. Specifically, the main characteristic of surface coating is the formation of a passivation layer to protect the electrode from direct contact with electrolyte, and the outstanding rate performance of the coated anode attributed to the excellent conductivity and intercalation kinetics [60,61]. In addition, the anode surface coating can also reduce the energy barrier for Li⁺ desolvation [62]. Ryota et al. [60] introduced the chemical vapor deposition approach to carbon coating with the mixture of vapor-grown carbon fibers and nanohorns, and further demonstrated that the decrease of SEI resistance improved the rate capability. Amorphous Al₂O₃-coated graphite anodes also exhibit excellent cycle stability at high rates, and the enhanced interfacial wettability improves the Li⁺ intercalation kinetics and capacity utilization of electrode material, as shown in Fig. 3b [61]. Similarly, the carbon-coated alternative anode materials TiNb₂O₇ demonstrated the high energy density and rate capability due to the improved electrical conductivity among the anode particles [63]. The application of composite electrode materials has attracted increasing attention in recent years, and its main advantage lies in the improved conductivity and enhanced charge transfer, while the high lithiation potential suppresses side reactions. Fig. 3a illustrates a composite anode material that is synthesized by incorporating the uniformly implanted amorphous silicon nanolayer and edge-site-activated, which improves the energy density and Li⁺ diffusion simultaneously [64]. The activated graphite edge doubles the reaction surface area, and the amorphous silicon coating improves the energy density with fast Li⁺ transport. Lithium titanium oxide (Li₄Ti₅O₁₂, LTO) exhibits the advantage of excellent rate capability, low-temperature electrochemical performance, thermal stability and the high lithiated potentials inhibiting lithium deposition [65]. However, lower energy density limits its application [66,67]. In addition, Red phosphorus (RP) exhibit the characteristics of high energy density and ideal lithiation potential, which facilitates it a potential candidate anode material with high rate capability. Li-ion batteries with red P/C nanocomposite anode have shown excellent rate performance [68]. For instance, Han et al. [69] fabricated a composite anode material synthesized by red phosphorus, carbon nanotubes and TiN nanosheets, which demonstrated that the excellent rate capability benefits from the in-situ conductive TiP₂ layer enhancing Li⁺ diffusion. In addition, the morphology control of electrode affects the rate capability of Li-ion batteries. Porous graphite as anode material was fabricated by catalyzed gasification as shown in Fig. 3c, which facilitated the rate capability by the increased Li⁺ ions transport [70]. Reducing the ion-path tortuosity is an effective strategy to accelerate Li⁺

Table 1
Analysis of typical strategies for rate capability improvement in anode.

Strategies	Description	Advantages	Conclusions
Surface coating	Synthesized the Al ₂ O ₃ coated graphite with core-shell structure via sol-gel method [61] TiNb ₂ O ₇ as anode material [63]	Improves Li ⁺ intercalation kinetics Improves the electrical conduction among particles Improves the Li ⁺ ions transport	The full cell recharged 84% SOC within 10 mins (6C) The full cell recharged 90% SOC within 6 mins (10C) 84% of initial capacity after 1500 cycles (5C)
Morphology control	Fabricated the porous graphite by MoO _x -catalyzed gasification [70] Fabricated the anodes with an out-of-plane aligned architecture via external magnetic field [71] Fabricated the three-dimensional graphite anode architecture with arrays of vertical pore channels [72] Fabricated the porous anodes by in-situ solvothermal reduction method [73] Fabricated the layered porous graphite via acid oxidation and KOH etching [74]	Reduces the tortuosity Improves the Li ⁺ ions transport Increases the porosity Improves the kinetics of Li ⁺ ions intercalation Improves the Li ⁺ ions transport	1.6 to 3 times faster charging than conventional graphite (2C) 86% of initial capacity after 600 cycles (6C) 60% of initial capacity after 3000 cycles (6C) High specific capacity (>300 mAh g ⁻¹) at current density of 100 mA g ⁻¹ 1.5 times faster charging than graphite anode without lithium plating
Doping	Incorporation of amorphous silicon nanolayer and edge-site-activated graphite [64] Fabricated the RP/C composite anode [68] Fabricated the TiP ₂ layer by embedding RP nanoparticles [69] Ge ⁴⁺ -doped Li ₄ Ti _{0.95} Ge _{0.05} O ₁₂ [78] Phosphorus-doped mesoporous carbons [79]	High lithiation potential and specific capacity Improves the Li ⁺ ions diffusion Enhances Li ⁺ insertion/extraction kinetics Improves Li ⁺ diffusion coefficient	The full cell recharged 84.1% SOC within 10 mins (6C) 92.6% of initial capacity after 200 cycles (3C) 98% of initial capacity after 50 cycles (10C) Specific capacities of 236 mAh g ⁻¹ at 8C

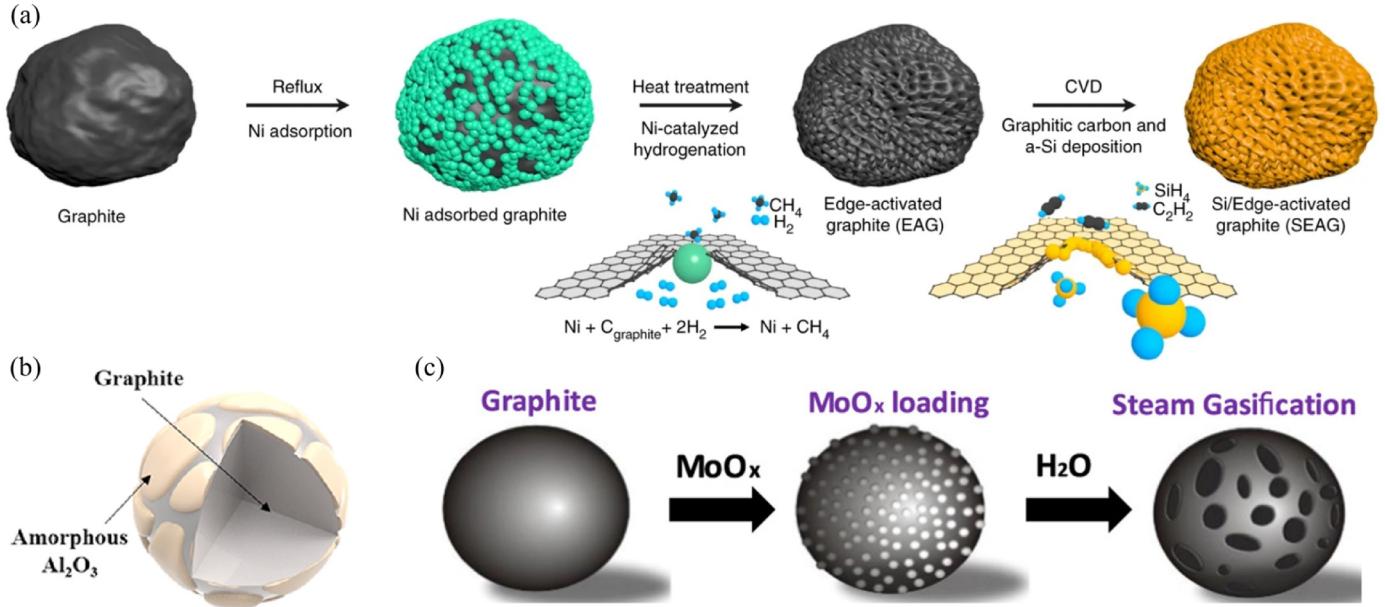


Fig. 3. Anode surface modification adopted to enhance rate capability. (a) A novel Si-Graphite composite material design enhancing lithium-ion kinetics. Reprinted from Kim et al. [64] with permission, Copyright 2017, Nature Communications. (b) Schematic illustration of Al_2O_3 coating on graphite surface. Reprinted from Deng et al. [61] with permission, Copyright 2016, Materials Letters. (c) Preparation of porous graphite anode by catalytic steam gasification. Reprinted from Deng et al. [70] with permission, Copyright 2016, Materials Letters. (TIFF format, 762 dpi*762 dpi, 2-column fitting image).

transport through the porous electrode, especially for thick electrodes required for high energy density. Fig. 4a illustrates the improved rate capability of graphite-based anode by an out-of-plane aligned architecture using external magnetic field, which reduce the tortuosity of the Li^+ path in anode and facilitates the diffusion at high C-rates [71]. Similarly, the fabrication of anode materials with porous channels or vertical channels have been demonstrated to be beneficial to rate capability. For example, the three-dimensional graphite anode structure with arrays of vertical pore channels facilitate the Li^+ ions transport [72]; The fabrication of porous anodes by in-situ solvothermal reduction method increased the porosity [73]; In addition, KOH etched layered porous graphite improved the kinetics of Li^+ ions intercalation and reduced the diffusion path among the interlayers [74,75].

The physical structure and chemical composition of the SEI exert profound effects on the rate performance of anode. Theoretically, an ideal SEI layer for fast charging should be thin, stable and possess excellent ion transportation [76]. In addition to the above optimization strategies in anode material, electrolyte modification provides the effective solution to enhance the migration kinetics of the Li^+ through SEI. Strategies of electrolyte modification will be reviewed in Section 2.2.

In order to suppress the lithium plating at high current densities and increase the energy density, novel anode materials with alternative composition are applied to the development of high-performance fast charging batteries. Wu et al. [77] investigated the rate capability of sulfurized polyacrylonitrile (SPAN) as anode material, which revealed that the higher lithiation potential of SPAN facilitates the exceptional cycling stability at high C-rates. Selective doping of trace chemical elements in anode materials to optimize the microstructure and charge state has proven to be beneficial to the rate capability [78,79]. For instance, the Ge-doped $\text{Li}_4\text{Ti}_{4.95}\text{Ge}_{0.05}\text{O}_{12}$ cubic spinel structure has greatly reduced the particle size and achieved excellent rate capability ascribe to the enhanced intercalation kinetics and decreased Li^+ diffusion path [78].

Apart from the battery material properties, the areal capacity of electrode also affects the rate capability. The areal capacity ratio of cathode to anode (C/A) of commercial Li-ion battery should be modified in accordance with the electrode properties for various

applications [80,81]. Essentially, higher C/A ratio means that there is a lack of sufficient accessible intercalation sites for Li^+ and may result in lithium plating under most of the charging operations, especially at high currents and at low temperatures. In contrast, lower C/A ratio suppresses lithium deposition but results in the overcharge of cathode [82]. In addition, high active surface area and porosity of anode can improve rate capability. Decreasing the thickness and increasing porosity of electrode are also beneficial to rate capability [71,83,84], which facilitates the diffusion of Li^+ through the porous electrode. The electrode thickness suitable for high C-rates tends to be thinner than the conventional thickness [80]. However, the decrease of electrode thickness deteriorates energy density. Fig. 4b illustrates the development of thick electrodes with low tortuosity design, which accelerates ion transport in thick electrodes with low-tortuosity pore structure [84]. In addition, novel anode with pore structure shortens the diffusion path of lithium ions with a larger porosity and high specific surface area, which exhibits the potential to improve rate capability [85,86].

2.1.2. Improvement in cathode

Improvements in cathode properties such as ionic and electronic conductivity also deliver great potential toward fast charging [34,87,88]. Essentially, the lithium concentration gradients aggravated by high current densities exacerbates the mechanical stress in electrode [89,90], especially in the case of non-uniform temperature scenarios. Cathode degradation primarily manifested in particle cracking [91], delamination of electrode layers [92] and fracturing between electrode particles and current collectors or binders [93,94]. Generally, the higher C-rate or the larger the particle size, the greater the possibility of particle cracking [91]. The rupture of electrode particles deteriorates the conductivity and integrity of the electrode. Even worse, the further reaction between the exposed fresh surface and electrolyte induce the LLI and loss of active materials (LAM). On the other hand, the electrolyte infiltrated into the cracks enable the diffusion of ions rather than electrons, which leads to the inhomogeneities current density distribution and aggravate cracking in turn. Therefore, smaller particles are less prone to cracking due to the lower lithium gradients [89,95].

In contrast to the anode, cathode materials with high rate capability are characterized by rapid Li^+ deintercalation and stable cycling.

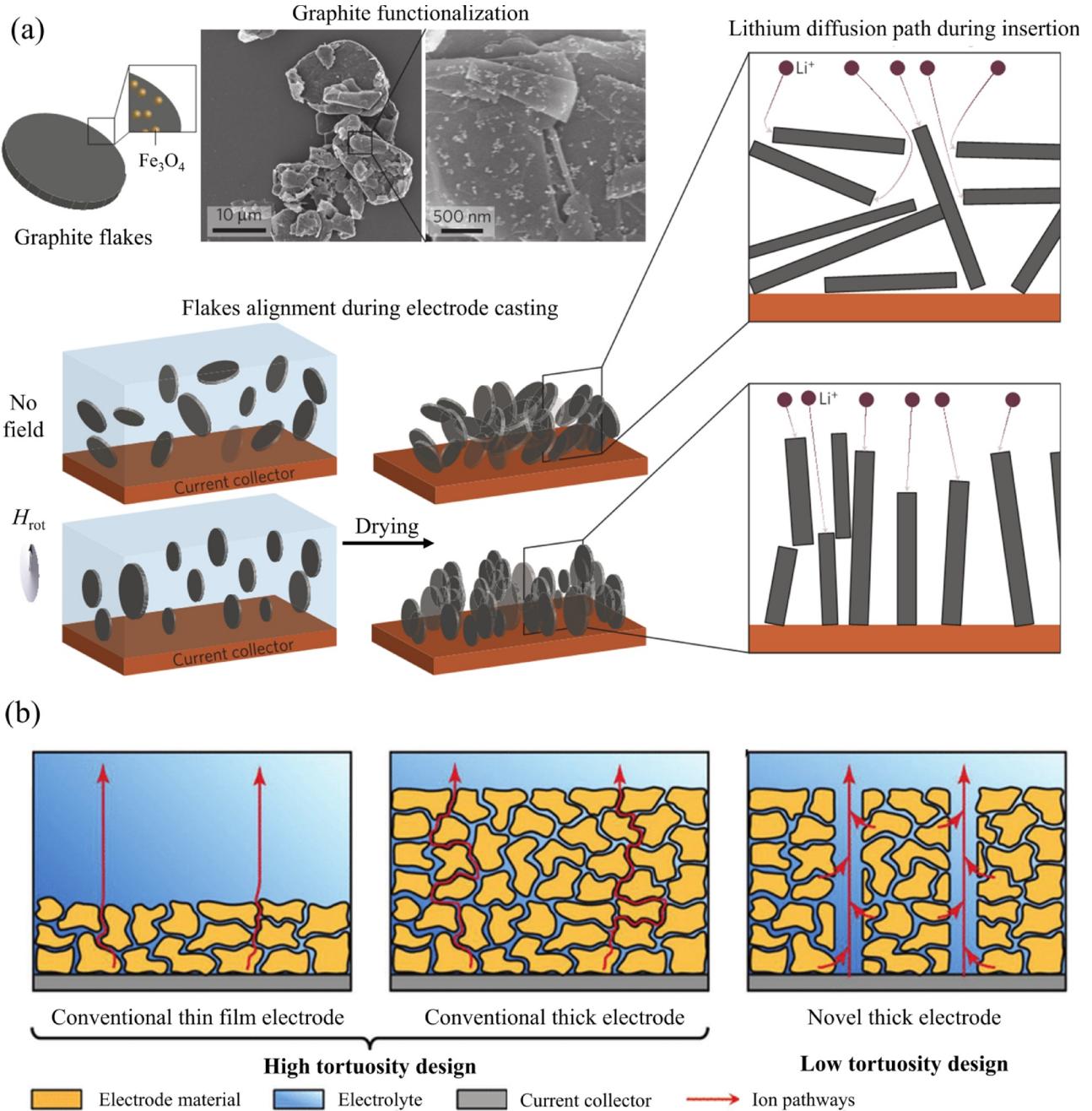


Fig. 4. Typical measures to accelerate the transfer of lithium ions in the electrode. (a) The application of magnetic field reduces the tortuosity of graphite flakes and shortens the lithium diffusion path. Reprinted from Juliette et al. [71] with permission, Copyright 2016, Nature energy. (b) Graphical illustration of a novel thick electrode that accelerates lithium ion transfer. Reprinted from Kuang et al. [84] with permission, Copyright 2019, Advanced energy materials. (TIFF format, 762 dpi*762 dpi, 1.5-column fitting image).

Optimization strategies include constructing short lithium diffusion pathways and providing high ionic conductive. Table 2 summarized the analysis of typical strategies for improving the rate capability in cathode. Surface coating facilitates the rate capability of cathode as well. For instance, the graphene-coated LiNi_{1/3}Co_{1/3}Mn_{1/3}O₂ exhibits excellent rate capability at high current densities, and it was demonstrated that the active materials formed by the graphene sheets facilitates the charge transfer, ionic transportation and ionic reversibility [96]. On the other hand, surface-coated cathodes also deliver excellent high-rate performance by enhancing interfacial kinetics. For instance, the ZrO₂-coated LiNi_{0.5}Mn_{1.5}O₄ exhibits better cycle stability at 6C charging rate, which is attributed to the reduced charge transfer resistance improving the interfacial kinetics [97]. Composite cathode

materials can obtain high-rate capability due to its optimized electrochemical property and layer-structured [98,99]. The freestanding LiFe_{0.2}Mn_{0.8}PO₄ (LFMP)/rGO nanocomposite delivers excellent cycle stability with high-rate charging ascribe to the high loading of active material of 83 wt%, and it was demonstrated that the fluffy structured LFMP nanoparticles reduced the tortuosity [99]. Cathode materials with gradient structure deliver excellent capacity retention at high current densities, which is attributed to the optimized electrochemical properties compared to intrinsic material [100,101]. For instance, Wen et al. [100] synthesized a novel LiMn_{1.912}Ni_{0.072}Co_{0.016}O₄ cathode encapsulated by a concentration-gradient shell, which was characterized by increasing Ni and Co while decreasing Mn concentration toward the particle surface. Electrochemical test revealed that the improved rate

Table 2

Analysis of typical strategies for rate capability improvement in cathode.

Strategies	Description	Advantages	Conclusions
Surface coating	Modified the $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ cathode with uniformly dispersed graphene nanosheets [96] Modified the $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ cathode with ZrO_2 coating [97]	Improves electronic conductivity Decreases the interfacial resistance	88.2% of initial capacity after 400 cycles (1C) 90.5% of initial capacity after 300 cycles (6C)
Gradient structured	Concentration-gradient shell encapsulated $\text{LiMn}_{1.912}\text{Ni}_{0.072}\text{Co}_{0.016}\text{O}_4$ [100]	Reduces the polarization and inner resistance	96% of initial capacity after 200 cycles (1C/55 °C)
	Fabrication of $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ cathode with full-gradient structure [101]	Improves the Li^+ diffusion coefficient	93.7% of initial capacity after 100 cycles (5C)
	$\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$ cathode with the gradient doping of phosphate polyanion [102]	Improves the Li^+ diffusion coefficient	92.9% of initial capacity after 50 cycles (2C/55 °C)
Doping	Fabricated the $\text{Li}(\text{Mn}_{1/3}\text{Ni}_{1/3}\text{Fe}_{1/3})\text{O}_2$ -Polyaniline composite cathode [98]	Improves the electronic conductivity	86% of initial capacity after 40 cycles (15C)
	Fabrication of $\text{Li}(\text{Fe}_{0.2}\text{Mn}_{0.8}\text{PO}_4)/\text{rGO}$ electrodes [99]	Reduces the tortuosity	74.7% of initial capacity after 50 cycles (5C)
	Modification of LiCoO_2 cathode by Mg^{2+} and Ti^{4+} co-doping [103]	Shortens the diffusion distance of Li^+	82.6% of initial capacity after 100 cycles (1C)
Physical method	Fabrication of LiFePO_4 cathode with redox-active fluoflavin polymer [104]	Decreases the electrode resistance	Ultrafast output (> 20 mA/cm ² at 30 C)
	Exposure of light to an operating LiMn_2O_4 cathode [105]	Reduces the energy required for Li^+ delithiation	Double the charging speed

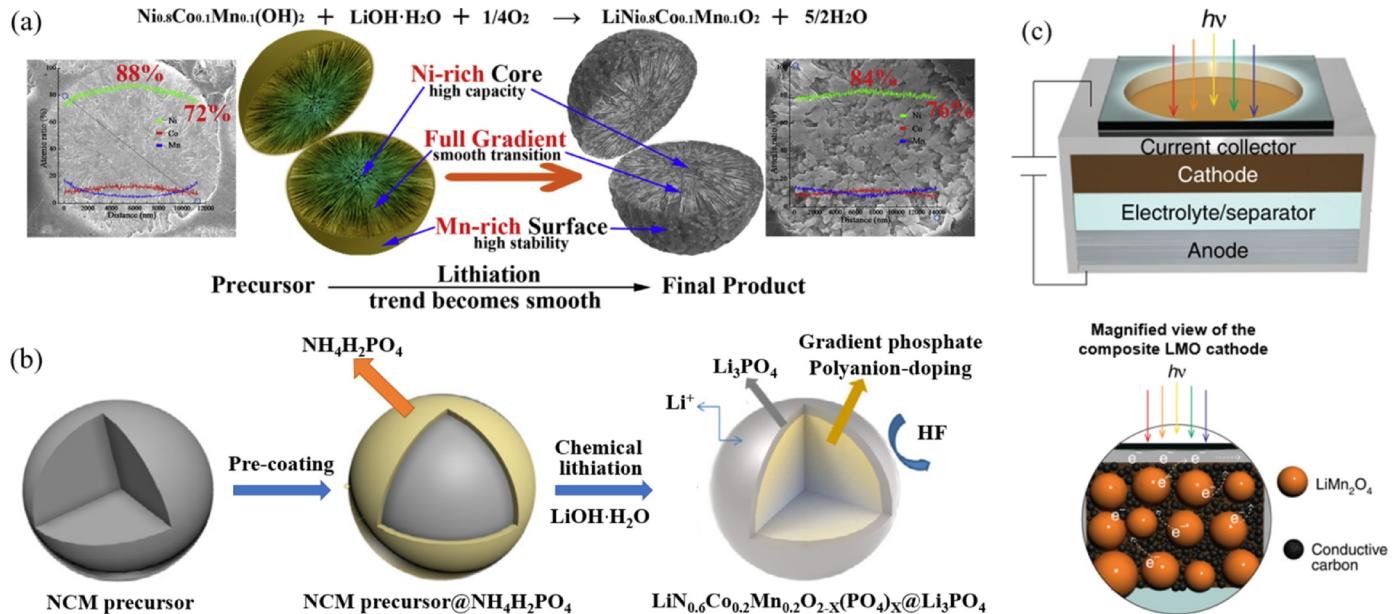


Fig. 5. Typical strategies to improve the rate capability of cathode. (a) Gradient doping strategy to improve cathode rate capability. Reprinted from Jiang et al. [101], with permission, Copyright 2019, *Electrochimica Acta*. (b) Schematic of the synthesis process of $\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_{2-x}(\text{PO}_4)_x@\text{Li}_3\text{PO}_4$ cathode. Reprinted from Ran et al. [102], with permission, Copyright 2019, *Electrochimica Acta*. (c) The principle of a photo-accelerated Li-ion battery. A direct exposure of light to an operating LMO cathode during charging, which results in more oxidized metal centers and ejected Li^+ are created under light and with voltage bias. Reprinted from Lee et al. [105] with permission, Copyright 2019, *Nature Communications*. (TIFF format, 762 dpi*762 dpi, 2-column fitting image).

capability is attributed to the reduced polarization and internal resistance. Fig. 5a shows that the full-gradient structured $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ cathode with the same concentration gradient distribution delivers high-rate charging capability, which is attributed to the enhanced lithium diffusion kinetics. Moreover, the improvement is more significant at higher current densities [101]. Fig. 5b illustrates a phosphate polyanion gradient doping to improve the rate performance of $\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$ cathode, and it was demonstrated that the Li_3PO_4 enhances the Li^+ diffusion coefficient and inhibits the dissolution of transition metal ions [102]. The strategy of element doping to improve the rate performance of cathode has been attracting increasing attention [103,104]. The Mg^{2+} and Ti^{4+} co-doping strategy improves the rate performance and high-voltage cycling stability of LiCoO_2 cathode. Specifically, the Mg^{2+} and Ti^{4+} optimized the particle size distribution and decreased charge transfer resistance, which enhanced

the Li^+ diffusion coefficient in cathode [103].

In addition to the above-mentioned modifications, enhancing the deintercalation of lithium ions in cathode via optical reaction provides an interesting suggestion towards fast charging. Fig. 5c illustrates a strategy for accelerating the charging rate of the cathode via interaction of cathode with white light. In particular, this enhancement is mainly attributed to the induction of a microsecond long-lived charge separated state, which results in more oxidized metal centers and ejected Li^+ under light and with voltage bias [105].

In brief, the trend of electrode optimization focuses on the electrode architectural design to improve the Li^+ intercalation kinetics, increase electronic conductivity and lithium-diffusion coefficient and shorten the Li^+ diffusion distance. In addition, novel materials chemistry and 3D cell architecture provide promising techniques for fast charging.

Table 3

Analysis of typical strategies for rate capability improvement in electrolyte.

Strategies	Description	Advantages	Conclusions
Electrolyte additives	Additive the isothiocyanate in LiPF ₆ -based electrolytes to scavenges HF and PF ₅ [110]	Reduces the R_{SEI}	91.8% of initial capacity after 300 cycles (2C)
	Additive the LiPF ₆ in dual-salt/carbonate-solvent-based electrolytes [111]	Forms a stable and conductive SEI	97.1% of initial capacity after 500 cycles (1C)
	Additive the diphenyl sulfone in EC/EMC/DEC (1:1:1) [112]	Improves lithium ion transport	75% of initial capacity after 500 cycles (5C)
	Additive the Non-aqueous LiPO ₂ F ₂ in EC/DMC (1:1) [113]	Reduces the R_{SEI} and R_{ct}	95.7% of initial capacity after 800 cycles (1C)
	Additive the Fluorosulfonyl isocyanate in EC/DMC (1:1) [114]	Reduces the R_{SEI}	Significantly increased the rate capability at low temperatures
	Additive the Methyl acetate in EC/EMC/DMC (5:1:14) [116]	Improves conductivity and reduces viscosity	Achieved better cycle stability at 2C charging
	Additive the allyl sulfide in EC/EMC/DMC (3:2:5) [117]	Reduces the R_{ct}	The reversible capacity was tripled at -30 °C without lithium plating
Highly concentrated electrolytes	Superconcentrated lithium bis(fluorosulfonyl)amide [120]	Improves the Li ⁺ intercalation and transference number t_+	The anode recharged 70% SOC within 30 mins
	Superconcentrated Acetonitrile solutions [121]	Increases the Li-ion transference number t_+	Enhanced the rate capability at various C-rates (20/C-5C)
Novel solvent compositions	Methyl formate [125]	Increases the ionic conductivity	Optimal the rate capability and cycling lifetime
	Dimethyl carbonate [126]	Increases the ionic conductivity	88.7% of initial capacity after 200 cycles (4C)
	Lithium bis(fluorosulfonyl)imide [127]	Improves conductivity and Li ion transference number t_+	84% of initial capacity after 500 cycles (5C)
	Butyronitrile: ethylene carbonate [130]	Increases the ionic conductivity	80% of initial capacity after 1000 cycles (1C)

2.2. Challenges for electrolyte

The properties of liquid electrolyte play a decisive role towards fast charging [106]. Routine electrolyte applied for Li-ion battery contains a mixture of organic solvents and lithium salt components, which dominates the migration kinetics of ions in electrolyte and electrode/electrolyte interface layer [34]. The ionic conductivity of electrolyte is not a key factor limiting the diffusion kinetics of lithium ion. However, the properties of SEI layer dominated by electrolyte composition significantly affect the rate capability. On the other hand, side reactions induced by fast charging also deteriorate electrolyte stability. Even worse, internal heat generation or lithium dendrites growth will deteriorate the conductivity of electrolyte and triggers exothermic reactions [60,113,114]. The electrolyte establishes a higher Li⁺ concentration gradient at high current densities, which may limit the available capacity of the battery in extreme cases. Therefore, it is essential to develop electrolytes with high-rate capability and safety [109].

Numerous studies have demonstrated the effects of electrolyte additives on improving rate capability and suppressing degradation [110–116], which is mainly attributed to the improved conductivity and decreased charge transfer resistance accelerating the ion transport. Modification of SEI properties by electrolyte additives has proven to be an effective solution to enhance the Li⁺ intercalation kinetics [110,111,113,114]. For instance, the addition of isothiocyanate to LiPF₆-electrolyte removed the reactive species such as HF and PF₅, which formed ion-transmittable and stable interfacial layers [110]. Electrolyte additives with high reduction potential such as fluorosulfonyl isocyanate (FI) facilitate the high-rate performance. Since the FI is reduced prior to the carbonate-based electrolyte, which formed the conductive SEI and reduced interfacial resistance [114]. On the other hand, it is of great significance to improve the rate performance of Li-ion batteries at low temperature. Allyl sulfate used as an electrolyte additive improves the rate capability of graphite anode at low temperatures, which is ascribed to the carbon-rich sulfur-containing film enhancing the charge transfer reaction [117]. In addition to the electrolyte additives, the application of highly concentrated electrolytes with high salt concentration exhibits the potential to improve the rate performance. The high transference number t_+ , high Li⁺

concentrations at the interface and excellent ion conducting SEI contribute to improve rate capability [118]. In addition, the highly concentrated of solvated structure may give rise to the Li⁺ transport mechanism with ligand exchange reaction, which accelerated the fast Li⁺ conduction [119]. For instance, the highly concentrated Acetonitrile-based electrolytes not only deliver enhanced reductive stability, but also increase the Li⁺ transference number t_+ and intercalation kinetics of reversible lithium [120,121].

Improving the electrolyte Li⁺ transference number t_+ is beneficial to increasing rate capability and power density of Li-ion batteries, especially for faster charging (>2C) [122]. Essentially, the ionic current allowed to be carried by Li⁺ is proportional to the Li⁺ transference number t_+ , and correspondingly the higher attainable SOC is prior to reaching the cutoff voltage with constant conductivity. Strategies to improving Li-ion transference bumber t_+ include the development of high Li⁺ transference number electrolytes, such as the application of nonaqueous polyelectrolyte solutions as liquid electrolytes [123], superconcentrated electrolytes [121]. The application of novel Li salts with larger ‘bulky’ anions can also improve the transference number but decrease the ionic conductivity [124]. Therefore, the development of the electrolyte with both high ionic conductivity and ion transfer number remains the ultimate goal of fast-charging.

Novel electrolyte solutions with high ionic conductivity and chemical stability demonstrated the excellent rate performance. For example, the application of novel organic co-solvents with low viscosity increases the ionic conductivity and lithium transference number t_+ [125–127]. Adding ester co-solvents can enhance ionic conductivity and improve the rate capability at low temperatures [128,129] and it is critical to optimize the lithium salt/solvent ratio to trade off the increased conductivity and cycling lifetime [125]. In addition, the enhancement of electrolyte conductivity in multi-temperature range needs to be stressed. Table 3 summarized the analysis of typical strategies for improving the rate capability in electrolyte.

In conclusion, the applications of low-viscosity co-solvents, high-concentration electrolytes, and additives that can obtain desirable SEI properties for fast charging are effective strategies to improve the high-rate charging of lithium-ion batteries. It should be emphasized that the rate capability and lifetime deserve careful evaluation in the study of

electrolytes. Meanwhile, the rate capability of these modified materials or construction approaches including electrodes and electrolytes is mostly explored on a laboratory scale, which may not be always translate into corresponding improvements in commercial batteries. Therefore, the multidisciplinary efforts are indispensable to enable fast charging of Li-ion batteries.

3. Thermal issues related with rate capability

3.1. Mitigating thermal-induced degradation

Although Li-ion battery exhibit high coulomb efficiency, energy loss associated with lithium intercalation and deintercalation in electrodes leads to internal heat generation [131,132]. The rate capability, safety and lifetime of battery are affected by the operation temperature [107,108,133]. In particular, thermal issues are greatly compounded at high rates [134]. Essentially, heat generation in battery can be divided into reversible and irreversible processes [135–137]. Ashkan and Siamak [132] investigated the processes of reversible and irreversible on total heat generation by a mathematical model, which suggested that the reversible heat dominants at low C-rates while the irreversible heat dominants at high C-rates. Meanwhile, the irreversible heat generation is proportional to the square of charging current, that is, heat generation increases with charging rates. Therefore, it is vital to manage internal resistances in cell to restrain heat generation during fast charging.

Most degradation mechanisms exhibit temperature dependence. Generally, high temperatures within the battery tend to accelerate side reactions. For example, the SEI growth at elevated temperatures diminishes the power and capacity ascribe to the increased interfacial kinetics resistance and LLI [133,138]. Even worse, the integrate passive layer disrupts and is decomposed exothermically at higher temperatures (above 60 °C) [24,139]. Zhang et al. [140] investigated the effects of current density and temperature on the stability of SEI layer, which demonstrated that heat generation induced by high current density is not conducive to the formation of stable SEI. Meanwhile, the interfacial kinetics resistance diminishes due to the improved ionic conductivity, which also indicates that interfacial stability and ionic conductivity are contradictory at high temperatures. High temperature-induced degradation includes material phase transition [93], gaseous by-product venting [37], binder decomposition [138] and metal dissolution [12,138]. In particular, the lattice expansion induced by high temperature aggravates volume swelling, and results in mechanical stress and even particle crack [141]. More extremely, the electrolyte may thermally decomposes with the elevated temperature and the resulting gaseous by-products exacerbate the mechanical stress in turn [142].

The impact of operation temperature on battery performance were usually evaluated based on the assumption of homogeneous distribution. However, in practical applications, the inhomogeneity of internal heat generation, conduction and dissipation can lead to temperature gradients within the battery [135]. Essentially, the thermal distribution at different locations within battery are inconsistent regardless of any geometry, which indicated that the temperature gradients is inevitable [134]. In particular, non-homogeneous heat conduction and dissipation in battery modules and packs aggravate temperature gradients [102]. The heat generation is mainly affected by current density, while the heat conduction and dissipation are dominated by cell chemistry and thermal management system (TMS). Especially for high C-rates, TMS should provide intelligent and efficient cooling to restrain temperature rise and minimize temperature gradients.

Temperature gradients also deteriorate battery performance, which exacerbates the inhomogeneities of side reaction rates and aging [15,143,144]. Song et al. [144] suggested that the severe temperature gradients significantly accelerate degradation and capacity fade due to

the difference of local stoichiometry in cathode. Zhu et al. [44] used a micro-Raman spectroscopy method to evaluate the effects of local high temperatures on cell performance. It should be noted that the enhanced surface current density induces temperature gradients and the localized-temperature hotspots contribute to the dendrite growth. Subsequently, suggestions were proposed to restrain local aging induced by temperature gradients from the perspective of TMS and battery design. In addition to the side reactions at micro level, excessively high temperature gradients may lead to particle cracking, local volume expansion of electrode and even laminate disintegration [28].

The worst thermal scenario is thermal runaway which is induced by the side reaction or temperature rise exceeding a certain limit within the battery [145]. Fast charging may induce thermal runaway. In recent years, nearly 30% of electric vehicle thermal runaway accidents are ascribed to improper fast charging. For example, a Tesla thermal runaway accident in Norway in 2016 was caused by internal short circuit while fast charging at a supercharger station [146]. Essentially, the safety concerns associated with fast charging are usually attributed to the exothermic reaction between lithium plating and electrolyte, which significantly decreases the triggering temperature of thermal runaway. Eventually, the thermal stability of the battery decreases after multiple charging abuse conditions. Especially in the pursuit of high energy density, it is worth exploring to improve the thermal stability of a cell with a high-nickel-content cathode in fast charging [145]. In addition, the growth of lithium dendrites may puncture the separator out, and results in internal short circuits, both of which pose the risk of thermal runaway. Meike et al. [47] investigated the thermal behavior of aged cell cycled at high-rates, which revealed that the initial self-heating temperature decreased after high-rates cycling. In addition, high rates charging at low temperatures result in hazardous situations ascribe to the lithium plating significantly increased self-heating rate during thermal runaway. Li et al. [42] investigated the thermal runaway mechanism of Li-ion battery after high-rate cycling, which revealed that both self-heating temperature (T_1), thermal runaway triggering temperature (T_2) and maximum temperature (T_3) decrease with the elevated C-rates. Subsequently, it is suggested that the exothermic reaction between plated lithium and electrolyte triggered thermal runaway. Furthermore, Ouyang's group investigated the evolution of thermal runaway in commercial NMC532/graphite cell. The exothermic reactions of lithium metal and electrolyte dominated the characteristic temperatures of thermal runaway evolution after fast charging, which triggers severe exothermic reaction above 110 °C [147].

Although sufficient attention has been paid to the safety of lithium-ion batteries, considerable efforts have been taken to suppress the decrease of thermal runaway triggering temperature and provide early warning [44,47]. However, it is difficult to eliminate the possibility of thermal runaway from improper fast charging in terms of the state-of-the-art technologies including material improvement [148–150] and battery management [151,152]. Real time observation of anode potential through reference electrode or battery model provides a potential solution [153,154]. Specifically, the dynamically adjusted charging profile maintains the anode potential higher than the threshold potential to avoid lithium plating, and then derives the non-destructive fast charging algorithm.

3.2. Preheating at low temperatures

Charging at low temperature tends to be inefficient and hazardous ascribe to high transfer resistance, poor ions conductivity, sluggish diffusivity of Li atoms [155]. The C-rates at low temperatures are usually limited by BMS to avoid severe degradation [156] and safety issues induced by dendrite growth. Yang et al. [157] employed a physics-based aging model to identify the characteristics of temperature-dependent degradation mechanism, which revealed that the appropriate temperature with minimal degradation rising from about 20 °C to 35–45 °C with the elevated C-rates. In other words, an appropriate

increase in ambient temperature is beneficial to fast charging. Madeleine et al. [158] performed a low-temperature aging tests of commercial Li-ion battery, which demonstrated that the degradation mainly ascribe to lithium plating induced capacity fade and resistance increase.

As previously described, electrolyte properties include composition, porosity, density and ionic conductivity significantly effects the rate capability [159]. The electrode/electrolyte interface kinetics are prone to be weakened ascribe to the inherent loss of conductivity and increased resistance of SEI at low temperatures. Increasing the diffusivity of lithium salt in electrolyte and solid-state lithium in graphite particle improve the rate capability at low-temperatures [160,161]. Smart et al. [160] investigated the electrode polarization with various electrolyte composition, which revealed that the SEI properties exhibits a critical impact on rate capability at low temperatures. Mohammed et al. [162] explored the mechanism of Li-ion battery charging performance affected by temperature, which revealed that the charge transfer resistance dominates the rate capability at low temperatures. Meanwhile, rate capability at moderate and high temperatures is primarily restricted by the lithium ion transport resistance. Subsequently, a self-heating strategy based on pulse current was proposed to improve the low temperature charging performance.

In brief, the degradation mechanism induced by low temperature charging is actually similar to moderate ambient temperature. However, the poor ionic conductivity in electrolyte and the sluggish interfacial transfer kinetics at low temperatures not only impose more strict restrictions on the C-rate, but also put forward higher requirements for charging optimization. More extremely, some Li-ion batteries are not recommended to be charged at sub-zero temperatures. Thus, the deteriorating battery performance in cold areas needs to be addressed urgently. Based on a coupled electrochemical-thermal model, Mukherjee et al. [163] explored the impact of electrode level microstructural on battery performance. It was revealed that the larger anode porosities compensate for the sluggish lithium transport kinetics in the electrolyte phases, and the self-heat during electrochemical charge can improve the charging performance at low temperatures. In addition to optimizing battery materials or limiting C-rates, preheating the battery to a charge-friendly temperature before charging has proved to be an effective improvement strategy [164,165]. However, it should be noted that the preheating temperature should be limited within an appropriate range to avoid further side reactions. In addition, the preheating efficiency should be high enough to shorten the total charging time.

The built-in heating device through the battery structure modification has proved to be an efficient approach of preheating [166–168]. In order to completely eliminate the lithium plating induced by low-temperature charging, Yang et al. [167] proposed a temperature-dependent controllable preheat system that enables intelligent current distribution between Ni foils (inside the cell for heating) and electrode (charging). As shown in Fig. 6a, a heating switch turns on automatically before charging in the case of cell temperature below the threshold that induced lithium plating. In contrast, the heating switch turns off and current is completely distributed for charging. The capacity loss after 4500 cycles at 3.5C in 0 °C was less than 20%, which significantly improved the low-temperature charging efficiency. However, the heating system inside the cell is so complicated that it is vital to verify the reliability. Generally speaking, a properly increasing in charging temperature can enhance the rate capability, but it may accelerate the side reactions inside battery [157]. In order to improve the rate capability at low temperatures and restrain the side reactions at high temperatures, a concept of asymmetric charging/discharging temperature to improve extreme fast charging (>6C) capability with minimal degradation was introduced in Ref. [169]. Specifically, pre-heat the battery rapidly rather than slowly before charging. The average temperature of the entire charging process is about 49 °C and the maximum temperature does not exceed 60 °C. The elevated temperature enhances kinetics and transport and eliminates Li plating. Meanwhile, the high temperature charging period is strictly limited to

less than 10 min to avoid serious material degradation (Fig. 6b).

Preheating the battery at low temperatures provides efficient and homogeneous heat distribution in charging, which reduces the workload of the cooling system simultaneously. However, the effects of heat generation on battery degradation should be further validated by cycle test or reliable battery models. In addition, the reliability of self-heating system through battery structural modification needs to be systematically evaluated. In brief, the application of low temperature pre-heating technology is promising, however, research on its performance and reliability is inevitable before commercialization.

4. Charging strategies advancement

Although extensive researches have been performed in materials to improve the rate capability of Li-ion battery. However, most of these studies are still in the stage of complex laboratory research, and there is no doubt that other engineering efforts are indispensable for commercial battery applications [170]. Therefore, it is of great significance to optimize the charging protocols of commercial Li-ion battery from the perspective of control.

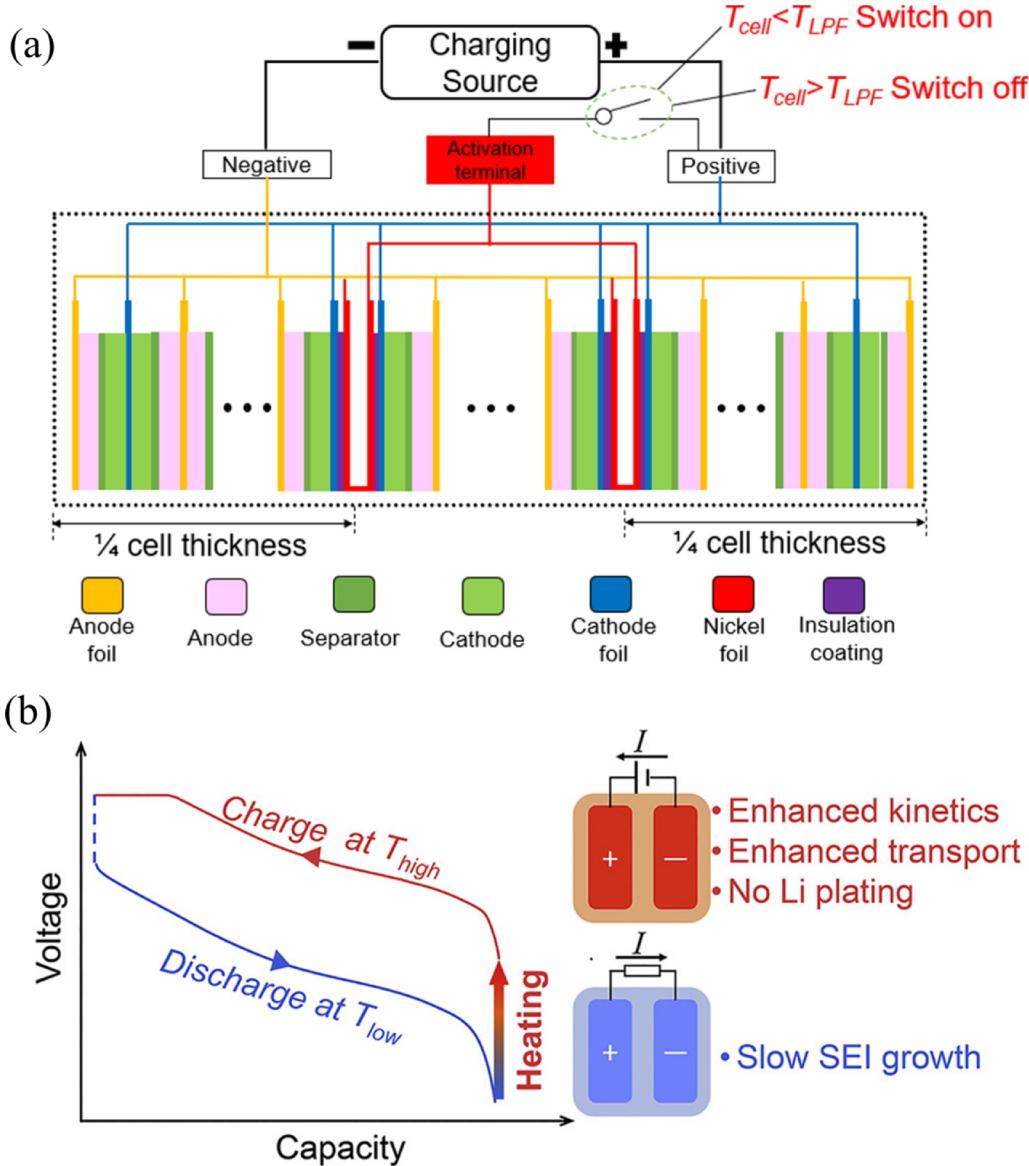
Tremendous efforts have been taken towards efficient and healthy charging of commercial Li-ion battery[17]. The charging protocols can be divided into passive charging and active charging according to whether the charging profile changes actively with the battery internal states. Essentially, the charging control should reduce the charging time with minimal degradation, which requires the combination of battery specifications such as nominal capacity, maximum C-rate, cut-off voltage and operation temperature [8,9]. In other words, the charging profile should be modified dynamically with the variation of internal states, which demonstrated the charging control is a complicated proposition.

4.1. Passive charging

In recent years, scholars have been devoted to exploring charging strategies that can improve charging efficiency, restrain degradation and ensure safety. Passive charging protocols were successively introduced such as constant current-constant voltage charging (CC/CV) [18], multistage constant current charging (MCC) [171], boost charging [18,172], varying current decay charging (VCD) [18], constant power-constant voltage (CP/CV) charging [12,173] and pulse charging [174–176].

CC/CV charging is the most widely used strategy for Li-ion batteries, which is charged with CC in initial until the cut-off voltage, and then kept with CV until 100% SOC. The CV charging can prevent the cell from overcharging and the charge current decreases gradually, which assures the lower degradation rate and safety. In addition, there are studies suggesting that CV charging at high SOC can realize re-intercalation of reversibly deposited lithium [177]. Although the charging time mainly depends on the charging rate of the CC stage, the higher charging current cannot reduce the charging time significantly due to the extension of CV stage [12]. The extension CV phase not only impedes further reduction of charging time, but also leads to higher overpotential of side reaction. Essentially, the main advantage of CC/CV charging protocol lies in the simplicity and ease of implement in BMS, but the higher charging current accelerates degradation. In short, increasing the charging current of the CC/CV protocol cannot meet the requirement of fast charging: shorten charging time and suppress degradation.

MCC charging belongs to the earlier types applied to fast charging. MCC protocol replaces the CV of the CC/CV protocol by a series of CC stage with a monotonically decreasing charging current, which is intended to suppress cell degradation. The charging current did not decrease to the next stage until the cut-off voltage reached with the preset minimum charging current. Compared with CC/CV protocol, the optimized MCC charging shortens charging time, suppresses temperature



rise and exhibits higher energy efficiency [178]. In addition, there is an alternative MCC protocol which is followed by the CV stage after the monotonically decreasing charging current. A short interval of CV charging in high SOC region decreased the current to inhibit excessive anode overpotential, heat generation and increase the charge capacity [171].

Boost charging is derived from the CC/CV protocol and characterized with high constant current charging during the initial stage [172]. The additional high charging current shortens charging time without inducing degradation due to the insensitive lithium plating in low SOC region. Therefore, the boost charging is more suitable for charging a fully discharged battery. However, there are inconsistent conclusions that boost charging accelerates degradation [18], which reveals that these charging protocols are not always applicable to batteries with different material systems.

VCD charging is complicated and flexible, which initiates with high-rate charging at low SOCs and applies nonlinear decay current to eliminate polarization. Subsequently, the cell voltage increases non-linearly until the cut-off voltage [179]. However, the VCD protocol exhibits a slight overcharge due to the transient overpotential. Therefore, it is necessary to keep the overpotential within the limited range to ensure safe and efficient charging [12].

Fig. 6. Preheating improves low temperature charging performance. (a) A temperature-dependent controllable preheat system that enables intelligent current distribution between Ni foils (inside the cell for heating) and electrode (charging). Heating switch turns on automatically before charging in the case of cell temperature below the threshold that induced lithium plating, otherwise, heating turns off and all current is distributed for charging [167]. (b) An asymmetric temperature modulation method is presented in which a Li-ion cell is rapidly pre-heated to and charged at ~ 60 °C, and the cell's exposure time to 60 °C is limited to ~ 10 min per cycle. The elevated temperature enhances kinetics and transport and hence eliminates Li plating, the limited exposure time to 60 °C avoids severe materials degradation. Reprinted from Yang et al. [169] with permission, Copyright 2019, Joule. (TIFF format, 762 dpi*762 dpi, 1-column fitting image).

CP/CV charging is initially charged with constant power and then switched to CV charging until the cut-off voltage [12]. Compared with conventional CC/CV charging, CP/CV protocol charged with high power at the initial charging stage to improve charging efficiency [173]. In addition, CP/CV charging can be adapted to battery systems with various voltage ranges. In recent years, it is being applied to the fast charging applications by more and more entrepreneurs.

All the above charging protocols are optimized based on the CC/CV charging. In addition, the pulse charging can periodically change the charging current and exhibit the advantage of eliminating polarization [180]. Compared with direct current charging, the pulse current can preferably maintain the stability of the anode interface and inhibit the growth of the passivation layer [176]. Aryanfar et al. [174] investigated the effect of pulse charging on lithium dendrites, which revealed that the lithium dendrite length on anode interface is shortened by 2.5 times compared to direct current charging. However, the pulse frequency is restricted to a certain range because the wider pulse current is not conducive to replenishment of Li^+ migration at dendrite tips timely. Therefore, an appropriate frequency range is critical in the application of pulse charging. However, the effect of pulse charging on battery performance is inconclusive too. Since the pulse current increases heat generation, high temperature accelerates side reactions within battery

simultaneously [175].

Essentially, the internal mechanism of battery varies with the charging time and cycles. The advantages of passive charging protocols are the simplicity of operation and ease of implementation in BMS, however, the internal state dependent parameters cannot be effectively controlled [18]. In addition, passive charging protocols are mostly empirical-based, extensive experimental data were absent to validate these claims and there was no interdependency between charging protocol and battery material system [173]. Therefore, passive charging tends to accelerate battery degradation and it is challenging to introduce an optimal charging strategy of commercial Li-ion battery. Meanwhile, the material characteristics, aging state and internal mechanism all put forward higher requirements for charging strategy with the advancement of battery technology. Based on these deficiencies, the development of charging protocols has extended to the active charging algorithm that considers both charging time and state of health (SOH).

4.2. Optimization based on battery physical characteristics

Some scholars considered the minimal thickness evolution or local volume swelling of pouch cell as a constraint indicator to optimize charging profiles [181–183]. Critical side reactions such as lithium deposition and SEI growth may cause changes in anode thickness [181,183]. Essentially, the electrode dominated the cell thickness and the anode changes more significantly than the cathode during intercalation and deintercalation [184]. In addition, inhomogenous degradation of the anode interface induce the non-uniform variation of irreversible thickness [185]. The impact of charging rates on thickness evolution of a commercial NMC/graphite pouch cell was investigated by a dial indicator measuring device [181]. The cell thickness increased slightly and disappeared promptly at low C-rates, while the thickness increased significantly and restored after a short duration at mild C-rates. Furthermore, the thickness increased irreversibly at high C-rates ascribe to the irreversible lithium plating, which demonstrated the feasibility of thickness measurement to indicate the lithium plating. The change of battery physical state in operation is taken as a constraint, Lu et al. [182] constrained the diffusion induced stress in battery and introduced an initial galvanostatic stage of high current before the conventional CC/CV charging. Subsequently, the amplitude and duration of the initial high-current stage are modified to accelerate charging and minimize mechanical stress. Similarly, Franz et al. [183] monitored the surface expansion of a commercial NMC/graphite pouch cell through laser triangulation under different operational conditions, which aims to evaluate the dependence of local volume swelling and lithium plating on anode. Subsequently, the charging profiles were optimized by monitoring the local expansion online.

In addition to the evolution of physical characterization, charging profile can also be optimized through aging experiments and model-based electrode structure design. For example, Stefan et al. [186] identified the minimal degradation charging profile of battery by experiment methodology design and derived the capacity fade by mechanical degradation analysis. To maximize usable energy, Campbell et al. [187] proposed a model-based methodology to determine the optimal electrode layers by considering thermal behavior. However, the complex experimental procedures and the needs for special designing software hindered its application. In brief, it is intuitive and convenient to detect side reactions such as lithium plating by the changes in external physical characteristics. Nevertheless, it is impossible to evaluate the degradation comprehensively and accurately in practical application, which is not conducive to fast and healthy charging. Meanwhile, a more systematic investigation of the electrochemical characteristics and degradation mechanism during charging is needed. On the other hand, this type of optimization is generally applicable to the pouch cells, which further restricts its application.

4.3. Model based charging optimization

Although the various aspects of battery performance can be evaluated by experiments, the high-cost and time-consuming tests can not be neglected. Battery models have been widely adopted in performance optimization, degradation mechanism analysis, state estimation and life prediction [17,188,189]. In order to extend the applicability of charging protocol, the model-based charging algorithms have gradually become a research hotspot. Essentially, the charging strategies integrate the battery model into the optimization framework, which constrains the shortest charging time and minimal degradation. Commonly-used models of Li-ion battery include the equivalent circuit models (ECMs) and Electrochemical models [190]. The ECMs simulate the external characteristics of battery that is widely adopted in BMS due to the simplicity. However, it cannot capture the internal states of the battery. In contrast, electrochemical models interpret the internal mechanism of battery and provides detailed information for performance optimization.

4.3.1. ECMs-based optimization

ECMs have been widely applied to the charging optimization of Li-ion batteries. Specifically, ECMs include Rint, First-order RC and Second-order RC model are used to describe cell behavior in charging. In addition to minimizing the charging time, the heat generation within battery and cycle life should be constrained as optimization objectives. The coupled thermal and aging model evaluate the health of the battery to derive the optimal charging strategy with health awareness. Model predictive control (MPC), genetic algorithm (GA), proportional-integral-derivative (PID) control, radau pseudo-spectral Method, dynamic programming (DP) algorithm, minimum-maximum strategy and particle swarm optimization (PSO) are used to solve single-objective or multi-objective optimization frameworks. The characteristics of ECMs-based optimization are maximizing charging efficiency, minimizing heat generation, reducing charging energy loss and accommodating to battery aging. In addition, advanced feedback controls are essential for the implementation of charging optimization.

The coupled electro-thermal-aging battery model combined with capacity fade analysis was used to derive a charging strategy with minimized capacity loss and it was demonstrated that the model parameters should be updated with SOC and cycles [191]. Charging optimization framework can be formulated as a linear time-varying model predictive control algorithm. Battery internal states including SOC and heat generation are estimated by nonlinear observer, which enabled the state-feedback control. Further, the optimization algorithm makes use of the battery internal dynamic information to optimally balance the charging duration and temperature rise [192]. The optimal charging profile should dynamically accommodate to different charging intervals. In order to restrain degradation induced by internal heat generation, both the charging duration and characteristic parameters were constrained to derive an universal voltage protocol based on a thermal model-coupled first-order ECM [193]. Subsequently, charging profile that can vary with SOC and SOH was derived, and it was demonstrated that the optimized charging protocol improves charging efficiency and results in best capacity retention [193,194]. Similarly, Wu et al. [195] took the charge time and energy loss as the optimization targets and adopted a dynamic programming algorithm to derive the optimal charging profile. The proportional-integral-derivative (PID) controller can modulate the charging profile in response to temperature rise and battery aging which shortens the charging duration without obvious temperature rise. Meanwhile, this closed-loop optimized design also provides potential for integrating it with BMS [196].

The health-conscious and fast charging protocol is a promising direction for optimization algorithm. For instance, Hu's group [197] established a multi-objective optimal control framework based on a coupled electro-thermal-aging model and explored a health-conscious fast-safe charging algorithm. Specifically, three charging regimes

including minimum-time charge, minimum-aging charge and balanced charge are investigated in detail. Subsequently, the optimal trade-off between the minimum charging duration and the minimal SOH decay is achieved by Legendre-Gauss-Radau (LGR) pseudo-spectral method.

Multi-objective particle swarm optimization (MOPSO) algorithm can be used to optimize battery charging strategy. Charging time, SOC and energy loss are constrained by multi-objective optimization and MOPSO is employed to satisfy various charging demands in Ref. [198]. Subsequently, a voltage-based multistage constant current charging strategy which significantly improves charging efficiency is proposed. Furthermore, the optimal charging profile of commercial NCA/Graphite lithium-ion batteries is obtained by MOPSO to trade off the charging duration and SOH. Compared with conventional charging, the proposed optimal charging can significantly shorten the charging time without accelerating aging [199]. The weight between charging time and temperature rise deserves detailed evaluation. Zhang et al. [200] proposed a charging optimization strategy that constrains the charging time and temperature rise. An enhanced thermal behavior model was introduced to improve the computational accuracy at high C-rates and the weighting coefficients of charging time and temperature rise were evaluated. Subsequently, the optimal charging profile was derived by genetic algorithm. Main features of ECM-based charging optimization are summarized in Table 4.

Essentially, the objectives of ECMs-based charging optimization are to improve the charging efficiency, eliminate cell polarization or restrain temperature rise. ECMs have been widely used in charging optimization due to its advantage of fast computation. However, the ECMs are unable to provide the internal fundamental mechanisms of Li-ion batteries such as intercalation/deintercalation, migration and diffusion of lithium ions. Meanwhile, side reactions such as the SEI growth and lithium plating are unable to be described by ECMs. On the other hand, ECMs-based charging optimization are mostly based on the fixed battery parameters, however, the battery parameters in real-world applications will inevitably change with battery aging [199]. Therefore, the model parameters should be updated with the charging process and battery state, otherwise, the optimized charging algorithm may lose

accuracy after certain cycles. Correspondingly, the charging optimization of Li-ion battery extends to the stage based on electrochemical models.

4.3.2. Electrochemical models based optimization

Electrochemical based models are widely used to optimize charging performance due to the ability to estimate internal states of Li-ion battery. Essentially, electrochemical models rest on the concentrated solution, porous electrode and kinetics equations, which exhibit significant advantages over ECMs accounting for internal electrochemical reaction mechanism ascribe to its physical based equations. The most widely used electrochemical-based models include pseudo two-dimensional model (P2D), single particle model (SPM) and reduced order electrochemical model (ROM).

The P2D model can be extended to various coupling models that provide high computational accuracy for charging optimization. For instance, a control-oriented electrochemical-thermal coupling model which constrains side reaction overpotential, electrolyte concentration, SOC and temperature was employed to formulate a linear time-varying model predictive control algorithm. As a result, the optimized charging strategy shortens the charging time and ensures health-related constraints simultaneously [203]. In order to maximize the charging efficiency and suppress heat generation, a P2D-based thermal coupling model was established to monitor the evolution of SEI growth and anode interfacial overpotential. Subsequently, an optimized multi-stage charging profile which varies with SOC and cycles was derived by dynamic programming optimization algorithm [204]. Further, in order to minimize capacity fade induced by SEI growth and maximize charging efficiency, an electrochemical-thermal-capacity fade coupled model was established to monitor the SEI potential and temperature rise, and the suboptimal charging current profiles was derived by the dynamic programming optimization technique. However, this optimization strategy cannot achieve the optimal balance between temperature rise and capacity fade [205].

Accurate and fast calculation in BMS is essential to capture the internal states in real time and achieve online application [190].

Table 4
Summary of main features of ECM-based charging optimization.

Battery model	Coupled model	Constraints	Optimization methods	Characteristic	Optimization results
Rint model [191]	Thermal/ Aging model	T_{Max} T_{end}	Model predictive control	ECM and capacity fade analysis are used to search for optimal charge profiles over the battery lifetime	Fast charging Less capacity loss Long cycle life
Second-order RC model [192]	Thermal model	SOC T V_{cell}	Model predictive control	Ensures satisfaction of all the health-related constraints	Reduced both the charging time and temperature rise
First-order RC model [193]	Thermal model	V_{cell} SOC q	Genetic algorithm	The optimum charging technique can accommodate cell aging	High charging efficiency Overvoltage prevention Easy implementation
First-order RC model [194]	Thermal model	T	Genetic algorithm	The charging time and temperature rise analyzed by genetic algorithm are optimally traded off	Reduced both the charging time and temperature rise
First-order RC model [195]	Energy loss model	Initial over-voltage	Dynamic programming algorithm	The charging time and battery energy loss are optimally traded off	Reduced the charging time and energy loss without capacity loss
First-order RC model [196]	Thermal model	V_{cell} T	Proportional-integral-derivative control	Employs a PID controller aided by a feed-forward term	20% faster charging with the same total temperature rise as CC–CV
Second-order RC model [197]	Thermal/ Aging model	SOC T_{core} $T_{surface}$	LGR pseudo-spectral method	The charging time and SOH subject to both electrical and thermal constraints	The optimized charging algorithm alleviated degradation with a slight time increase
First-order RC model [198]	Energy loss model	SOC $Charging\ time$	MOPSO	Investigates the impact of the number of charging stages, cut-off voltage and weight factors	Significantly improved charging performance
First-order RC model [199]	Thermal/ Aging model	V_{cell} SOC $T_{surface}$	MOPSO	Multi-objective optimization to balance charging duration and SOH	Decreased the charging duration by 43.4% with negligible SOH increase
First-order RC model [201]	Thermal model	V_{cell} T	Aronsson operator	Minimizes maximum irreversible heat	Reduced the heat generation and charging duration by 37.5% and 43% respectively
First-order RC model [202]		V_{cell} T	LGR Pseudo-spectral Method	Charging time and charging energy loss are optimally traded off	Accommodates with aging and exhibits the advantage of energy-saving

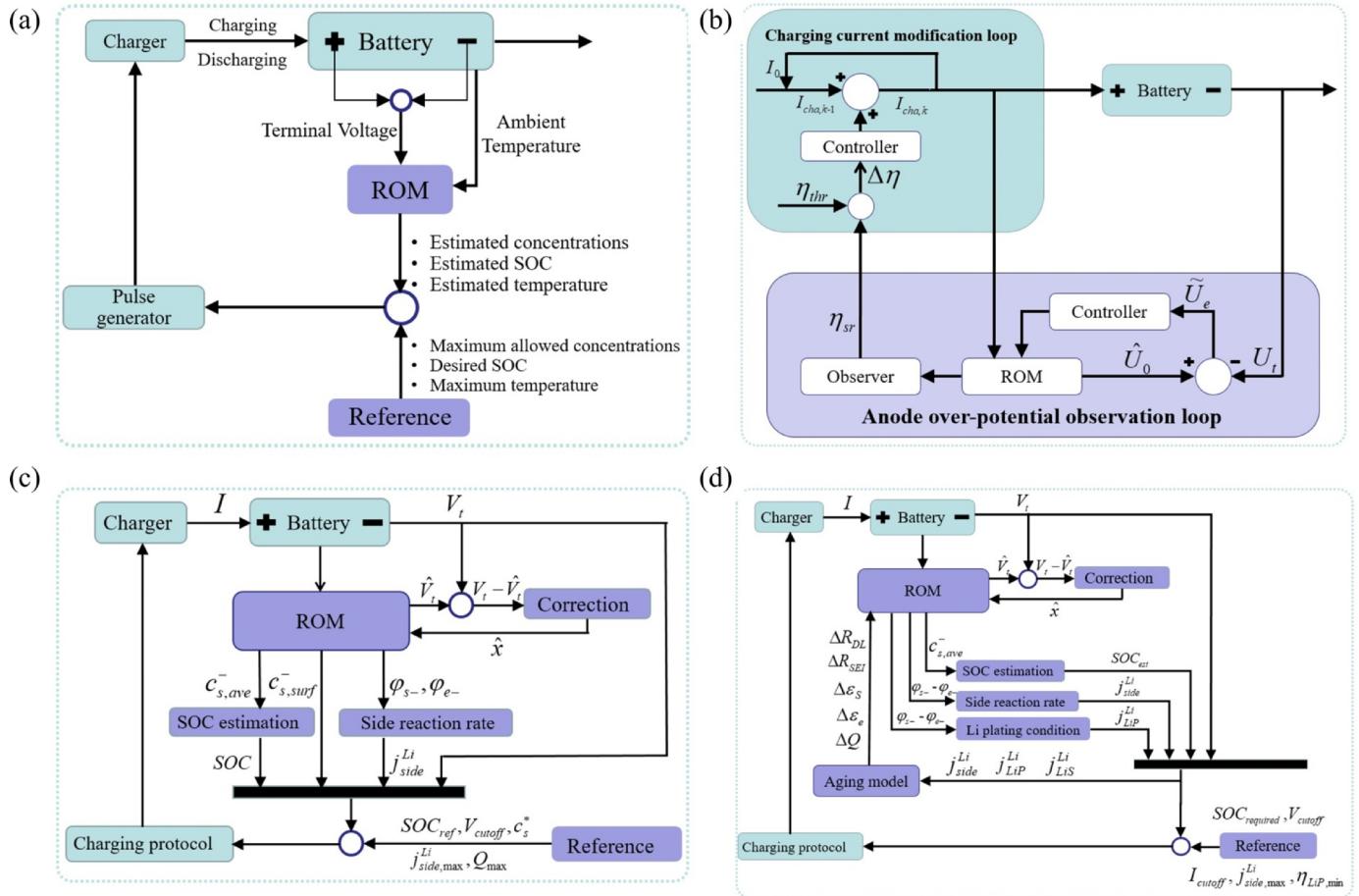


Fig. 7. Charging optimization based on reduced order electrochemical model. (a) Surface ion concentration and SOC are used for active control of charging current, the inputs for the ROM are the time varying charging or discharging current, terminal voltage and ambient temperature, the outputs of the ROM are the surface concentration of negative electrode, SOC and terminal voltage. Once the reference values for SOC and concentration are set at a maximum allowable temperature, the charging profile can be determined based on the differences between the reference and the estimated variables from the ROM [217]. (b) The ROM is used to observe the over-potential at the negative anode/separator interface online, the difference between the observed anode over-potential and predetermined threshold potential is used as an additional feedback signal, which ensuring the observed anode over-potential as close to the threshold potential as possible during charging [153]. (c) Charging optimization based on ROM that considering the limiting factors include surface ion concentration, SOC, cut-off voltage and side reaction rate [221]. (d) Charging optimization based on a ROM with extended Kalman filter that considering the constraints of anode potential, side reaction rate and cut-off voltage [214]. (TIFF format, 762 dpi*762 dpi, 2-column fitting image).

However, the full order P2D model is too sophisticated to provide the internal states of battery on-board [206]. Specifically, the main drawbacks of full order electrochemical models include: 1) High computational complexity; A fundamental P2D model was coupled with several sets of partial differential and dynamic equations. Therefore, a complete analytical solution of the full order P2D model equation is inaccessible [190]. 2) The parameters of a full order P2D model is too numerous to identify accurately, which include characteristic geometric parameters, electrochemical and physical parameters of materials. Meanwhile, most parameters are difficult to calibrate through experiments and can only be estimated, calculated and obtained through published literatures [207]. In brief, the full order electrochemical model is inappropriate for control-oriented implementation. Correspondingly, it is urgent to develop electrochemical models achieve a faster computational speed with similar fidelity [208].

The single particle model is a simplified version of full order P2D model [209], which assumed that the concentration and potential of Li^+ in electrolyte phase remains constant and the anode/cathode are represented by two spherical particles. Specifically, the Li^+ transfer from cathode to anode instantaneously during charging and the local current density is substituted by average current density. However, the kinetic equation in electrolyte is ignored. Although these assumptions

significantly reduce the computational cost, the simulation accuracy in state estimation and performance optimization is limited, especially for the operation of high current density [210–212].

Since the SP model neglects electrolyte phase limitations, the simulation at high rates ($>1\text{C}$) is inaccurate due to the limiting factor of concentration gradients in the liquid phase [189]. This also indicates that there is a compromise between the computational efficiency and the simulation accuracy. In contrast, the simplified full-order P2D model can reduce the computational demand and retaining sufficient accuracy. Meanwhile, the drawbacks of the full order P2D model and SPM have prompted the development of ROM [213]. For example, the partial differential equations in full order P2D model are simplified to ordinary differential equations and the nonlinear equations was linearized to derive a reduced model, which significantly improved computing efficiency without sacrificing fidelity. Simplification techniques including transfer function, polynomial profile, galerkin approximation and residual grouping were applied to various applications, which satisfied the corresponding accuracy requirements such as the real-time control, performance optimization, age prediction and state estimation. For instance, simplification of electrochemical model based on the assumption of the uniform active material utilization, which employed a model-order reduction procedure based on Padé approximation to

simplify the partial differential equations (PDEs) to ordinary differential equations. Both the diffusion kinetics of solid and liquid phase exhibit nonlinear transfer characteristics that enable the mathematical structure of simplified model suitable for control [214]. For another instance, the simplification of electrochemical model by polynomial approximation for electrolyte variables and multi-particle model with variable solid-state diffusivity at the particle level [215]. Analysis of the pore wall flux distribution and the development of approximate methods can also be applied to simplify electrochemical models [216], which not only achieved the precisely estimation of the potential and current density distribution, but also satisfied the ability of online state estimation by simulating the side reaction rates.

Since the internal states of the battery varies with charging, the most promising charging optimization strategy should compensate for the disturbances and uncertainties of the model based on a closed loop [17]. From the perspective of optimization strategies, the internal state observer based on simplified electrochemical model is essential to describe the internal properties of Li-ion battery. Meanwhile, a real-time controller inputs the requested reference values (such as current, voltage, maximum side reaction rate, maximum surface ion concentration and temperature) into the model and updates states parameters by comparing the reference with the estimated values. Subsequently, the charging profile is derived by optimization algorithm. From the perspective of optimization objectives, the optimal charging should have the shortest charging time with health-aware performances. Therefore, charging optimization based on simplified electrochemical models on the premise of restraining side reactions has drawn increasing attention. For instance, the dynamically estimation of ion concentration at the anode/electrolyte interface by a reduced order electrochemical model to derive a charging current that avoid excessive ion concentrations at the electrodes [217]. Fig. 7a illustrates that both the SOC derived from average ion concentration of electrodes and the surface ion concentration were applied to the charging optimization, which shortens the charging time and reduces capacity loss induced by LLI.

Minimizing the temperature rise during fast charging is critically important to prevent abusive conditions and extend battery life potentially. Charging optimization based on ROM which constrained the internal state variables including SOC, ions concentration in solid phase, cell temperature, molar flux and overpotential is capable of shortening the charging time and maintaining the temperature constraint [218]. The optimal control principle was derived by a closed loop algorithm with state feedback, which characterized by high charging efficiency and maintained internal states such as the heat generation within safe limits.

As mentioned previously, lithium plating is the critical side reaction mechanism that accelerates degradation of the graphite-based anode in Li-ion battery at high C-rates. Essentially, there are two effective approaches to mitigate lithium plating from the perspective of control. One is that the chemical re-intercalation and stripping of reversible lithium can restore the active lithium during the discharge or rest duration [49]. However, irreversible lithium loss is inevitable and the strategy is difficult to implement in BMS [207]. The other is that lithium plating is strictly suppressed by the real-time control of anode overpotential [153,154,219,220]. Since the internal resistance and the capacity fade vary with charging time and lifetime, numerous researches have shown that the adaptive charging profile accommodating to the battery internal states is beneficial to shortening charging time, reducing capacity fade, improving energy efficiency, restraining side reaction and keeping temperature within a desirable range. In particular, the continuous estimated anode potential as the indicator of lithium plating to inhibit side reactions, which provides a promising direction for non-destructive fast charging [220]. Constructing a closed-loop observer of the lithium deposition state based on the ROM and using the state feedback to modify the charging profile online is an effective non-destructive fast charging algorithm [153]. The optimized charging algorithm adaptively modified in real time by maintaining the

observed anode overpotential just above the preset threshold slightly, as shown in Fig. 7b. However, there is no degradation model coupled into the optimization framework. Therefore, the model parameters never updated to accommodate the variation of internal states.

Based on the simplified electrochemical model, the surface ion concentration, state of charge, cut-off voltage and side reaction rate are considered as constraints, and the maximum surface ion concentration and side reaction rate are used to modify the charging profile with minimal degradation, as shown in Fig. 7c. Subsequently, the optimized charging strategy is verified in the Battery-In-The-Loop system [221]. Further, a simplified electrochemical model coupled of side reaction, lithium plating and stripping was developed and the estimated anode potential, side reaction rate and cut-off voltage were constrained to derive a new fast charging strategy, as shown in Fig. 7d. The real-time verification of the battery-in-the-loop system indicates that the optimized charging strategy reduces the charging time while maintaining the degradation rate [154].

On the other hand, fast charging at low temperatures tends to be more challenging due to the sluggish electrochemical kinetics. An electrochemical model coupled with a zero-dimensional thermal model can be applied to charge optimization over a wide range of temperatures [222–224]. Specifically, the characteristic lies in the introduction of a semi-quantitative degradation factor related to the local anode potential which describes the potential degradation mechanism in wider temperature ranges. In addition, the strategy of actively controlling the operating temperature can optimize charging and suppress degradation. Nonlinear model predictive control determines the optimal charging currents at different SOCs and derives the optimal temperature with respect to degradation rates, which significantly reduced the charging duration and minimized degradation [224]. Main features of ECM-based charging optimization are summarized in Table 5.

4.4. In-situ monitoring-based optimization

The in-situ anode potential measurement method can be applied to detecting and quantifying lithium plating, which provides a feasible strategy for the development of fast charging without lithium deposition. Recent years, the anode potential controlled charging optimization based on the three-electrode cell configuration have been attracting increasing attention [219]. The amount of lithium plating can be quantified based on the measured anode potential to identify the impact of lithium plating on battery degradation at different C-rates [226]. Moreover, it is critically important to develop a charging algorithm that satisfies the shortest charging duration with minimal degradation. Specifically, the anode potential is directly controlled through the reference electrode and limited to a positive value to avoid lithium plating, and the charging current is controlled to maximize the charging efficiency [227]. Meanwhile, this strategy is more effective for improving low-temperature charging performance. As a new method to eliminate lithium plating, this in-situ measurement also provides inspiration for the further development of advanced battery management systems.

4.5. Data-driven charging optimization

Performance optimization of Li-ion battery based on experimental analysis and model simulation has been widely recognized. However, the time-consuming experimental procedure and complex modeling also limit the further development of optimal charging control. For example, it may take several months to assess the cyclic performance of battery. In the era of big data, charging optimization based on machine learning and cloud control has shown unique advantages in advanced intelligent algorithms and reduced experimental costs, which has attracted increasing attention. In order to reduce the optimization cost, the closed-loop optimization system based on big data has been

Table 5

Summary of main features of Electrochemical model-based charging optimization.

Battery model	Coupled model	Constraints	Characteristic	Optimization Results
P2D [152]	Thermal/Aging model	η_{SEI} T ϵ_{cf} V_{cell}	Develops an electrochemical-thermal-capacity fade coupled model and employed DP optimization	Reduced the capacity fade by 4.6% and the temperature rise by 16.3%, respectively
ROM [153]		η_{anode} I_{Max} V_{cell}	Maintains the observed anode over-potential close to the pre-set threshold potential	96.8% of the capacity could be charged within 52.5 mins without lithium deposition
ROM [154]	Aging model	η_{anode} j_{side}^{Li} V_{cell}	Applies a ROM with EKF to estimate anode potential, side reaction rate and cutoff voltage	Reduced the charging time of 50% than 2C CC/CV charging with comparable capacity loss
P2D [203]	Thermal model	SOC c_e η_{anode} T V_{cell}	Formulates a linear time-varying predictive control and employed a moving horizon estimation to monitor internal state	Reduced the charging time while ensuring the satisfaction of health-related constraints
P2D [204]	Thermal model	T SOC V_{cell}	Develops an electrochemical thermal coupled model to predict the heat generation rate, charging energy rate, and temperature rise	Achieved lower temperature rise and higher charging efficiency
SPM [218]		I_{Max} T V_{cell}	Applies Pontryagins principle to derive optimal control and simulated in a closed loop fashion with state feedback	Reduced the charging time and maintained the temperature rise within limits
ROM with EKF [221]	Aging model	$c_{s,surf}$ j_{side}^{Li} V_{cell}	Applies a ROM with EKF to estimate maximum surface ion concentration and side reaction rate	Reduced the charging time of 40% than 1C CC/CV charging with comparable degradation
ROM [223]	0D thermal model	I_{Max} V_{cell}	Develops a data-driven model-reduction method with high approximation quality	A significant reduction of charging time at low temperatures
ROM [224]	Aging model	SOC I_t V_{cell}	Optimizes the charging current by nonlinear model predictive control and actively controlling the working temperature	Reduced the charging time of 61% than 1 C CC/CV charging with comparable degradation
SPM with electrolyte dynamics [225]	Aging model	$c_{s,surf}$ SOC c_e V_{cell}	Formulates a multi-objective optimal framework and employed a dynamic programming (DP)	Reduced the charging time without sacrificing battery health

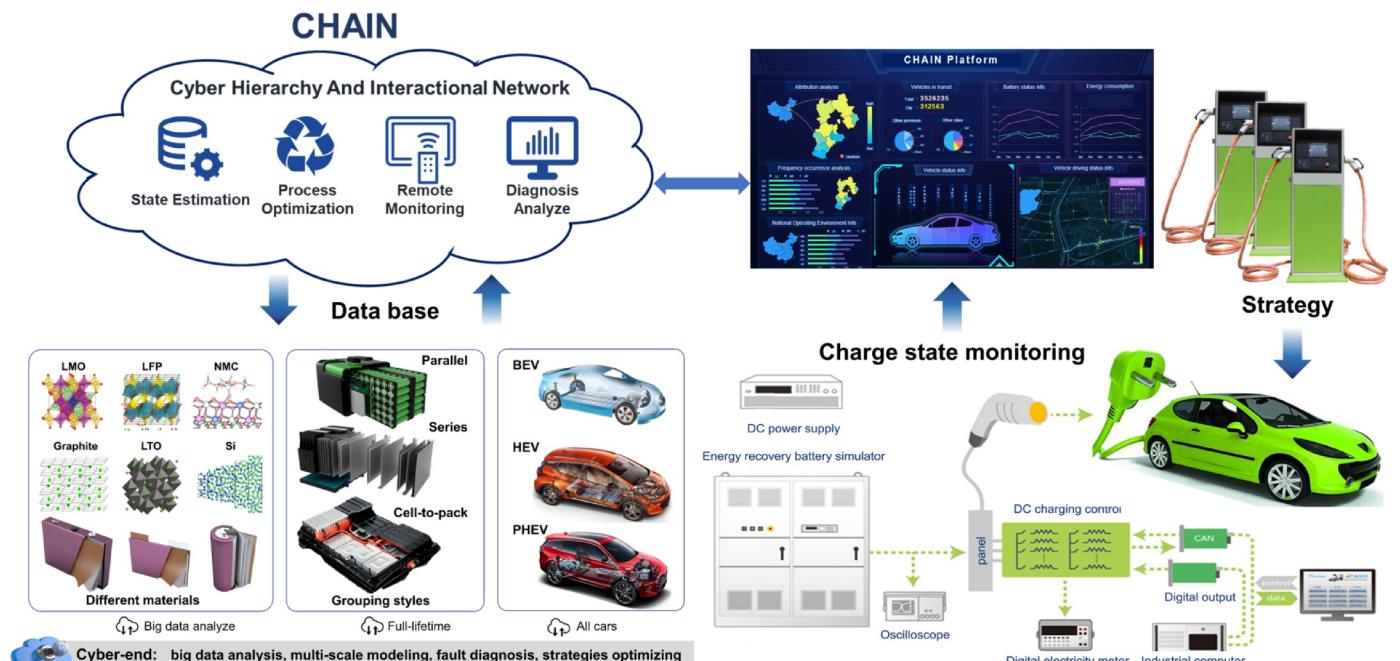


Fig. 8. Schematic diagram of multi-condition charging control based on CHIAN. The BMS in the vehicle-end generates enormous datasets throughout real-time monitoring, state estimation, safety and fault prognosis, encrypted and uploaded to the cyber-end simultaneously. Real-time monitoring is essential to optimize the charging profile. Reprinted from Yang et al. [233] with permission, Copyright 2020, Matter. (TIFF format, 762 dpi*762 dpi, 2-column fitting image).

introduced [228–234]. The charging optimization approach based on machine learning provides new solutions [228]. For instance, the cycle life of battery was maximised the optimization of parameter space with a specified charging step and duration. Meanwhile, the experimental data of first few cycles were applied to predicting the final cycle life which reduced the time consumption per experiment. Subsequently, the Bayesian optimization algorithm was adopted to detect the parameter space of charging protocols which simplified the experimental procedures. The proposed methodology rapidly determined fast charging protocols with minimal degradation among 224 candidates within 16 days. In contrast, exhaustive search without early prediction takes over 500 days. For another instance, Yang's group proposed a digital solution for battery lifespan management based on cyber hierarchy and interactional network (CHAIN) [233]. The closed-loop optimization system integrating with the cloud platform, and real-time monitoring and analysis of massive data to predict battery performance by adjusting parameters, as shown in Fig. 8. Meanwhile, the closed-loop chain based on material synthesis, characterization, electrochemical mechanism and safety enables dynamic management and performance optimization. Based on the big data analysis in CHAIN, the fast charging strategy can be iteratively optimized according to the full-lifespan degradation process and inconsistency of performance.

5. Summary and outlook

Range anxiety and time-consuming charging have been imposed restrictions on the promotion of EVs for a long time, the implementation of fast charging, which improves the convenience, is a promising research hotspot. Optimized solutions to improve the rate capability were discussed in view of materials, thermodynamics and control, which depends on in-depth understanding of internal mechanism at high C-rates. Essentially, efforts to improve the rate capability should be dedicated to multi-scale consideration. For example, improve the electrode properties to enhance interface kinetics and shorten diffusion distance; implement electrolyte with excellent migration kinetics and chemical stability; develop intelligent and easy-to-implement TMS to restrain temperature rise and gradient; establish simplified and multiphysics coupling-based electrochemical model to indicate the battery internal states more comprehensively and accurately without sacrificing computational efficiency; optimize charging strategy towards efficient and healthy charging. Although great progress has been made, further efforts are desired in the following issues.

- 1) SEI layer with excellent ion conductivity and stability is a prerequisite for fast charging, while the properties of SEI is dominated by the electrolyte composition. Therefore, it is essential to develop the electrolyte additives to form an interfacial layer with compact morphology and stable property as well as sufficiently ionic conductivity. Meanwhile, solid electrolytes exhibit potential benefits in ions conductivity and restrain flammability, however, special structure modification is needed to address the issue of solid–solid contact and interface stability. At the electrode level, electrode architectural modification can reduce the distance of ion-diffusion and sustain structure stability. In addition, novel anode materials with nanoporous structure for fast reaction kinetics need to be developed to restrain lithium deposition. However, it is worth noting that potential degradation mechanism, stability, manufacturing technique and cost of new electrode materials have yet to be bridged.
- 2) To achieve the health and safety for high temperature applications, TMS should be optimized to limit the temperature rise and gradient within the optimum operating range during fast charging. Develop new materials and electrode forms to mitigate thermal runaway. On the other hand, the effect of internal preheating on improving low-temperature charging has been validated in many literatures, while the frequency and amplitude of AC depending on cell chemistry need to be further optimized. In addition, the impact of internal

preheating on the degradation and reliability of battery should be critically evaluated.

- 3) The multiphysics coupling model should be developed to describe the internal mechanism variations more comprehensively. Developing simple, robust and computationally efficient reduced-order models without sacrificing accuracy is a constant pursuit. Meanwhile, it is essential to determine and rank the most influential parameters in simplified models for charge optimization. For example, applying high-order polynomial fitting simplifies the most complicated parameter variables of solid-phase diffusion along the radial direction of electrode particles. In addition, we should pay more attention to the crucial safty-related side reactions such as lithium plating and dendrite growth. Adaptive charging based on models monitoring lithium plating and lithium stripping in real-time should be developed.
- 4) It is promising to develop a universal charging protocol which can extend to various types of battery. The closed-loop battery state observer and current controller based on simplified electrochemical model or three-electrode cell configuration will be a hotspot in the foreseeable future. On the other hand, the implementation cost of charging algorithm in hardware should be evaluated and it is significant to develop a real-time optimization algorithm that can be simulated in BMS without sacrificing accuracy.
- 5) In the era of big data, data-driven machine learning is gradually applied to materials determination, charging optimization, state estimation and fault diagnosis. Future research should concentrate on the development of intelligence machine learning algorithms and performance optimization on the basis of reducing experimental costs through high-throughput screening and in-depth data analysis.

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.

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References

- [1] Y. Sun, N. Liu, Y. Cui, Promises and challenges of nanomaterials for lithium-based rechargeable batteries, *Nat. Energy.* 1 (2016) 1–12, <https://doi.org/10.1038/nenergy.2016.71>.
- [2] S. Chu, A. Majumdar, Opportunities and challenges for a sustainable energy future, *Nature* 488 (2012) 294–303, <https://doi.org/10.1038/nature11475>.
- [3] B. Dunn, H. Kamath, J.M. Tarascon, Electrical energy storage for the grid: a battery of choices, *Science* 334 (2011) 928–935, <https://doi.org/10.1126/science.1212741>.
- [4] B. Scrosati, J. Garche, Lithium batteries : status, prospects and future, 195 (2010) 2419–2430. 10.1016/j.jpowsour.2009.11.048.
- [5] A. Meintz, J. Zhang, R. Vijayagopal, C. Kreutzer, S. Ahmed, I. Bloom, A. Burnham, R.B. Carlson, F. Dias, E.J. Dufek, J. Francfort, K. Hardy, A.N. Jansen, M. Keyser, A. Markel, C. Michelbacher, M. Mohanpurkar, A. Pesaran, D. Scoffield, M. Shirk, T. Stephens, T. Tanim, Enabling fast charging – Vehicle considerations, *J. Power Sources* 367 (2017) 216–227, <https://doi.org/10.1016/j.jpowsour.2017.07.093>.
- [6] G. Hunt, USABC Electric Vehicle Battery Test Procedures Manual, USA United States Dep. Energy, Washington, DC, 1996.
- [7] YDB 195-2018, Technical Requirements and Test Method For Quick Charge of Mobile Telecommunication Terminal Equipment, CHINA MIIT, 2018.
- [8] J. Deng, C. Bae, A. Denlinger, T. Miller, Electric vehicles batteries: requirements and challenges, *Joule* 4 (2020) 511–515, <https://doi.org/10.1016/j.joule.2020.01.013>.
- [9] S. Ahmed, I. Bloom, A.N. Jansen, T. Tanim, E.J. Dufek, A. Pesaran, A. Burnham, R.B. Carlson, F. Dias, K. Hardy, M. Keyser, C. Kreutzer, A. Markel, A. Meintz, C. Michelbacher, M. Mohanpurkar, P.A. Nelson, D.C. Robertson, D. Scoffield, M. Shirk, T. Stephens, R. Vijayagopal, J. Zhang, Enabling fast charging – A battery technology gap assessment, *J. Power Sources* 367 (2017) 250–262, <https://doi.org/10.1016/j.jpowsour.2017.06.055>.

- [10] T. Ohsaki, T. Kishi, T. Kuboki, N. Takami, N. Shimura, Y. Sato, M. Sekino, A. Satoh, Overcharge reaction of lithium-ion batteries, *J. Power Sources* 146 (2005) 97–100, <https://doi.org/10.1016/j.jpowsour.2005.03.105>.
- [11] P. Bauer, N. Stemberger, J. Doppler, P. Kumar, Battery modeling and fast charging of EV, Proc. EPE-PEMC 2010-14th Int. Power Electron. Motion Control Conf. 2010, <https://doi.org/10.1109/EPEPEMC.2010.5606530>.
- [12] A. Tomaszecka, Z. Chu, X. Feng, S. O'Kane, X. Liu, J. Chen, C. Ji, E. Endler, R. Li, L. Liu, Y. Li, S. Zheng, S. Vetterlein, M. Gao, J. Du, M. Parkes, M. Ouyang, M. Marinescu, G. Offer, B. Wu, Lithium-ion battery fast charging: a review, *ETransportation* 1 (2019) 100011, , <https://doi.org/10.1016/j.etran.2019.100011>.
- [13] D. Anseán, M. Dubarry, A. Devie, B.Y. Liaw, V.M. García, J.C. Viera, M. González, Fast charging technique for high power LiFePO₄ batteries: a mechanistic analysis of aging, *J. Power Sources* 321 (2016) 201–209, <https://doi.org/10.1016/j.jpowsour.2016.04.140>.
- [14] S.F. Schuster, T. Bach, E. Fleder, J. Müller, M. Brand, G. Sextl, A. Jossen, Nonlinear aging characteristics of lithium-ion cells under different operational conditions, *J. Energy Storage* 1 (2015) 44–53, <https://doi.org/10.1016/j.est.2015.05.003>.
- [15] Y. Troxler, B. Wu, M. Marinescu, V. Yuft, Y. Patel, A.J. Marquis, N.P. Brandon, G.J. Offer, The effect of thermal gradients on the performance of lithium-ion batteries, *J. Power Sources*. 247 (2014) 1018–1025, <https://doi.org/10.1016/j.jpowsour.2013.06.084>.
- [16] M. Armand, Issues and challenges facing rechargeable lithium batteries, 414 (2001) 359–367.
- [17] Y. Gao, X. Zhang, Q. Cheng, B. Guo, J. Yang, Classification and review of the charging strategies for commercial lithium-ion batteries, *IEEE Access* 7 (2019) 43511–43524, <https://doi.org/10.1109/ACCESS.2019.2906117>.
- [18] P. Keil, A. Jossen, Charging protocols for lithium-ion batteries and their impact on cycle life-An experimental study with different 18650 high-power cells, *J. Energy Storage* 6 (2016) 125–141, <https://doi.org/10.1016/j.est.2016.02.005>.
- [19] B. Kang, G. Ceder, Battery materials for ultrafast charging and discharging, *Nature* 458 (2009) 190–193, <https://doi.org/10.1038/nature07853>.
- [20] Y. Liu, Y. Zhu, Y. Cui, Challenges and opportunities towards fast-charging battery materials, *Nat. Energy* 4 (2019) 540–550, <https://doi.org/10.1038/s41560-019-0405-3>.
- [21] A.S. Mussa, A. Liivat, F. Marzano, M. Klett, B. Philippe, C. Tengstedt, G. Lindbergh, K. Edström, R.W. Lindström, P. Svens, Fast-charging effects on ageing for energy-optimized automotive LiNi_{1/3}Mn_{1/3}Co_{1/3}O₂/graphite prismatic lithium-ion cells, *J. Power Sources* 422 (2019) 175–184, <https://doi.org/10.1016/j.jpowsour.2019.02.095>.
- [22] P. Verma, P. Maire, P. Novák, A review of the features and analyses of the solid electrolyte interphase in Li-ion batteries, *Electrochim. Acta* 55 (2010) 6332–6341, <https://doi.org/10.1016/j.electacta.2010.05.072>.
- [23] T.R. Jow, S.A. Delp, J.L. Allen, J.P. Jones, M.C. Smart, Factors limiting Li⁺ charge transfer kinetics in li-ion batteries, *J. Electrochem. Soc.* 165 (2018) A361–A367, <https://doi.org/10.1149/2.1221802jes>.
- [24] M.-T.F. Rodrigues, G. Babu, H. Gullapalli, K. Kalaga, F.N. Sayed, K. Kato, J. Joyner, P.M. Ajayan, A materials perspective on Li-ion batteries at extreme temperatures, *Nat. Energy* 2 (2017) 1–14, <https://doi.org/10.1038/nenergy.2017.108>.
- [25] A. Mistry, F.L.E. Usseglio-Vireta, A. Colclasure, K. Smith, P.P. Mukherjee, Fingerprinting redox heterogeneity in electrodes during extreme fast charging, *J. Electrochem. Soc.* 167 (2020) 090542, , <https://doi.org/10.1149/1945-7111/ab8fd7>.
- [26] 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>.
- [27] C. Mao, R.E. Ruther, J. Li, Z. Du, I. Belharouak, Identifying the limiting electrode in lithium ion batteries for extreme fast charging, *Electrochim. Commun.* 97 (2018) 37–41, <https://doi.org/10.1016/j.elecom.2018.10.007>.
- [28] K. Takahashi, V. Srinivasan, Examination of graphite particle cracking as a failure mode in lithium-ion batteries: a model-experimental study, *J. Electrochem. Soc.* 162 (2015) A635–A645, <https://doi.org/10.1149/2.0281504jes>.
- [29] M.F. Lagadec, R. Zahn, V. Wood, Characterization and performance evaluation of lithium-ion battery separators, *Nat. Energy*. 4 (2019) 16–25, <https://doi.org/10.1038/s41560-018-0295-9>.
- [30] R. Zahn, M.F. Lagadec, M. Hess, V. Wood, Improving ionic conductivity and lithium-ion transference number in lithium-ion battery separators, *ACS Appl. Mater. Interfaces*. 8 (2016) 32637–32642, <https://doi.org/10.1021/acsami.6b12085>.
- [31] S. Goriparti, E. Miele, F. De Angelis, E. Di Fabrizio, R. Proietti Zaccaria, C. Capiglia, Review on recent progress of nanostructured anode materials for Li-ion batteries, *J. Power Sources* 257 (2014) 421–443, <https://doi.org/10.1016/j.jpowsour.2013.11.103>.
- [32] S. Choi, G. Wang, Advanced lithium-ion batteries for practical applications: technology, development, and future perspectives, *Adv. Mater. Technol.* 3 (2018) 1–21, <https://doi.org/10.1002/admt.201700376>.
- [33] N. Nitta, F. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: present and future, *Mater. Today*. 18 (2015) 252–264, <https://doi.org/10.1016/j.mattod.2014.10.040>.
- [34] G.L. Zhu, C.Z. Zhao, J.Q. Huang, C. He, J. Zhang, S. Chen, L. Xu, H. Yuan, Q. Zhang, Fast charging lithium batteries: recent progress and future prospects, *Small* 15 (2019) 1–14, <https://doi.org/10.1002/smll.201805389>.
- [35] Z. Li, J. Huang, B. Yann Liaw, V. Metzler, J. Zhang, A review of lithium deposition in lithium-ion and lithium metal secondary batteries, *J. Power Sources* 254 (2014) 168–182, <https://doi.org/10.1016/j.jpowsour.2013.12.099>.
- [36] X.G. Yang, Y. Leng, G. Zhang, S. Ge, C.Y. Wang, Modeling of lithium plating induced aging of lithium-ion batteries: transition from linear to nonlinear aging, *J. Power Sources* 360 (2017) 28–40, <https://doi.org/10.1016/j.jpowsour.2017.05.110>.
- [37] X. Han, L. Lu, Y. Zheng, X. Feng, Z. Li, J. Li, M. Ouyang, 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>.
- [38] L. Yang, X. Cheng, Y. Gao, Y. Ma, P. Zuo, C. Du, Y. Cui, T. Guan, S. Lou, F. Wang, W. Fei, G. Yin, Lithium deposition on graphite anode during long-term cycles and the effect on capacity loss, *RSC Adv.* 4 (2014) 26335–26341, <https://doi.org/10.1039/c4ra02096k>.
- [39] T.C. Bach, S.F. Schuster, E. Fleder, J. Müller, M.J. Brand, H. Lorrmann, A. Jossen, G. Sextl, Nonlinear aging of cylindrical lithium-ion cells linked to heterogeneous compression, *J. Energy Storage* 5 (2016) 212–223, <https://doi.org/10.1016/j.est.2016.01.003>.
- [40] V. Zinth, C. Von Lüders, M. Hofmann, J. Hattendorff, I. Buchberger, S. Erhard, J. Rebelo-Kornmeier, A. Jossen, R. Gilles, Lithium plating in lithium-ion batteries at sub-ambient temperatures investigated by in situ neutron diffraction, *J. Power Sources* 271 (2014) 152–159, <https://doi.org/10.1016/j.jpowsour.2014.07.168>.
- [41] X. Li, A.M. Colclasure, D.P. Finegan, D. Ren, Y. Shi, X. Feng, L. Cao, Y. Yang, K. Smith, Degradation mechanisms of high capacity 18650 cells containing Si-graphite anode and nickel-rich NMC cathode, *Electrochim. Acta*. 297 (2019) 1109–1120, <https://doi.org/10.1016/j.electacta.2018.11.194>.
- [42] Y. Li, X. Feng, D. Ren, M. Ouyang, L. Lu, X. Han, Thermal runaway triggered by plated lithium on the anode after fast charging, *ACS Appl. Mater. Interfaces*. 11 (2019) 46839–46850, <https://doi.org/10.1021/acsami.9b16589>.
- [43] M. Ouyang, Z. Chu, L. Lu, J. Li, X. Han, X. Feng, G. Liu, Low temperature aging mechanism identification and lithium deposition in a large format lithium iron phosphate battery for different charge profiles, *J. Power Sources*. 286 (2015) 309–320, <https://doi.org/10.1016/j.jpowsour.2015.03.178>.
- [44] Y. Zhu, J. Xie, A. Pei, B. Liu, Y. Wu, D. Lin, J. Li, H. Wang, H. Chen, J. Xu, A. Yang, C.L. Wu, H. Wang, W. Chen, Y. Cui, Fast lithium growth and short circuit induced by localized-temperature hotspots in lithium batteries, *Nat. Commun.* 10 (2019) 1–7, <https://doi.org/10.1038/s41467-019-09924-1>.
- [45] T. Waldmann, B.I. Hogg, M. Wohlfahrt-Mehrens, Li plating as unwanted side reaction in commercial Li-ion cells – a review, *J. Power Sources* 384 (2018) 107–124, <https://doi.org/10.1016/j.jpowsour.2018.02.063>.
- [46] A. Friesen, F. Horsthemke, X. Mönnighoff, G. Brunklaus, R. Krafft, M. Börner, T. Risthaus, M. Winter, F.W. Schappacher, Impact of cycling at low temperatures on the safety behavior of 18650-type lithium ion cells: combined study of mechanical and thermal abuse testing accompanied by post-mortem analysis, *J. Power Sources* 334 (2016) 1–11, <https://doi.org/10.1016/j.jpowsour.2016.09.120>.
- [47] M. Fleischhammer, T. Waldmann, G. Bisle, B.I. Hogg, M. Wohlfahrt-Mehrens, Interaction of cyclic ageing at high-rate and low temperatures and safety in lithium-ion batteries, *J. Power Sources* 274 (2015) 432–439, <https://doi.org/10.1016/j.jpowsour.2014.08.135>.
- [48] T. Waldmann, M. Wohlfahrt-Mehrens, Effects of rest time after Li plating on safety behavior—ARC tests with commercial high-energy 18650 Li-ion cells, *Electrochim. Acta*. 230 (2017) 454–460, <https://doi.org/10.1016/j.electacta.2017.02.036>.
- [49] B. Epding, B. Rumberg, H. Jahnke, I. Stradtmann, A. Kwade, Investigation of significant capacity recovery effects due to long rest periods during high current cyclic aging tests in automotive lithium ion cells and their influence on lifetime, *J. Energy Storage* 22 (2019) 249–256, <https://doi.org/10.1016/j.est.2019.02.015>.
- [50] J. Wandt, P. Jakes, J. Granwehr, R.A. Eichel, H.A. Gasteiger, Quantitative and time-resolved detection of lithium plating on graphite anodes in lithium ion batteries, *Mater. Today* 21 (2018) 231–240, <https://doi.org/10.1016/j.mattod.2017.11.001>.
- [51] L. Lu, X. Han, J. Li, J. Hua, M. Ouyang, A review on the key issues for lithium-ion battery management in electric vehicles, *J. Power Sources* 226 (2013) 272–288, <https://doi.org/10.1016/j.jpowsour.2012.10.060>.
- [52] C. von Lüders, V. Zinth, S.V. Erhard, P.J. Osswald, M. Hofmann, R. Gilles, A. Jossen, Lithium plating in lithium-ion batteries investigated by voltage relaxation and in situ neutron diffraction, *J. Power Sources* 342 (2017) 17–23, <https://doi.org/10.1016/j.jpowsour.2016.12.032>.
- [53] J.C. Burns, D.A. Stevens, J.R. Dahn, In-Situ Detection of Lithium Plating Using High Precision Coulometry, 162 (2015). 10.1149/2.0621506jes.
- [54] X. Zhao, Y. Yin, Y. Hu, S.Y. Choe, Electrochemical-thermal modeling of lithium plating/stripping of Li(Ni_{0.8}Mn_{0.2}Co_{0.2})O₂/Carbon lithium-ion batteries at subzero ambient temperatures, *J. Power Sources* 418 (2019) 61–73, <https://doi.org/10.1016/j.jpowsour.2019.02.001>.
- [55] H. Wu, D. Zhuo, D. Kong, Y. Cui, Improving battery safety by early detection of internal shorting with a bifunctional separator, *Nat. Commun.* 5 (2014) 1–6, <https://doi.org/10.1038/ncomms6193>.
- [56] T. Waldmann, M. Kasper, M. Wohlfahrt-Mehrens, Optimization of charging strategy by prevention of lithium deposition on anodes in high-energy lithium-ion batteries - electrochemical experiments, *Electrochim. Acta*. 178 (2015) 525–532, <https://doi.org/10.1016/j.electacta.2015.08.056>.
- [57] D. Ren, K. Smith, D. Guo, X. Han, X. Feng, L. Lu, M. Ouyang, J. Li, Investigation of lithium plating-stripping process in Li-ion batteries at low temperature using an electrochemical model, *J. Electrochim. Soc.* 165 (2018) A2167–A2178, <https://doi.org/10.1149/2.0661810jes>.
- [58] U.R. Koleti, C. Zhang, R. Malik, T.Q. Dinh, J. Marco, The development of optimal charging strategies for lithium-ion batteries to prevent the onset of lithium plating at low ambient temperatures, *J. Energy Storage* 24 (2019) 100798, , <https://doi.org/10.1016/j.est.2019.100798>.

- [org/10.1016/j.est.2019.100798](https://doi.org/10.1016/j.est.2019.100798).
- [59] K. Xu, A. Von Cresce, U. Lee, Differentiating contributions to “ion transfer” barrier from interphasial resistance and Li⁺ desolvation at electrolyte/graphite interface, *Langmuir* 26 (2010) 11538–11543, <https://doi.org/10.1021/la1009994>.
- [60] R. Yuge, N. Tamura, T. Manako, K. Nakano, K. Nakahara, High-rate charge/discharge properties of Li-ion battery using carbon-coated composites of graphites, vapor grown carbon fibers, and carbon nanohorns, *J. Power Sources* 266 (2014) 471–474, <https://doi.org/10.1016/j.jpowsour.2014.05.068>.
- [61] D.S. Kim, Y.E. Kim, H. Kim, Improved fast charging capability of graphite anodes via amorphous Al₂O₃ coating for high power lithium ion batteries, *J. Power Sources* 422 (2019) 18–24, <https://doi.org/10.1016/j.jpowsour.2019.03.027>.
- [62] S. Komaba, T. Ozeki, K. Okushi, Functional interface of polymer modified graphite anode, *J. Power Sources* 189 (2009) 197–203, <https://doi.org/10.1016/j.jpowsour.2008.09.092>.
- [63] N. Takami, K. Ise, Y. Harada, T. Iwasaki, T. Kishi, K. Hoshina, High-energy, fast-charging, long-life lithium-ion batteries using TiNb₂O₇ anodes for automotive applications, *J. Power Sources* 396 (2018) 429–436, <https://doi.org/10.1016/j.jpowsour.2018.06.059>.
- [64] N. Kim, S. Chae, J. Ma, M. Ko, J. Cho, Fast-charging high-energy lithium-ion batteries via implantation of amorphous silicon nanolayer in edge-plane activated graphite anodes, *Nat. Commun.* 8 (2017) 1–10, <https://doi.org/10.1038/s41467-017-00973-y>.
- [65] H.G. Jung, M.W. Jang, J. Hassoun, Y.K. Sun, B. Scrosati, A high-rate long-life Li₄Ti₅O₁₂/Li[Ni_{0.45}Co_{0.1}Mn_{0.45}]O₄ lithium-ion battery, *Nat. Commun.* 2 (2011) 515–516, <https://doi.org/10.1038/ncomms1527>.
- [66] M. Odziomek, F. Chaput, A. Rutkowska, K. Świerczek, D. Olszewska, M. Sitarz, F. Lerouge, S. Parola, Hierarchically structured lithium titanate for ultrafast charging in long-life high capacity batteries, *Nat. Commun.* 8 (2017) 1–7, <https://doi.org/10.1038/ncomms15636>.
- [67] S. Wang, W. Quan, Z. Zhu, Y. Yang, Q. Liu, Y. Ren, X. Zhang, R. Xu, Y. Hong, Z. Zhang, K. Amine, Z. Tang, J. Lu, J. Li, Lithium titanate hydrates with superfast and stable cycling in lithium ion batteries, *Nat. Commun.* 8 (2017), <https://doi.org/10.1038/s41467-017-00574-9>.
- [68] Y. Sun, L. Wang, Y. Li, Y. Li, H.R. Lee, A. Pei, X. He, Y. Cui, Design of red phosphorus nanostructured electrode for fast-charging lithium-ion batteries with high energy density, *Joule* 3 (2019) 1080–1093, <https://doi.org/10.1016/j.joule.2019.01.017>.
- [69] X. Han, Z. Zhang, M. Han, Y. Cui, J. Sun, Fabrication of red phosphorus anode for fast-charging lithium-ion batteries based on Ti/N/TiP₂-enhanced interfacial kinetics, *Energy Storage Mater.* 26 (2020) 147–156, <https://doi.org/10.1016/j.ensm.2019.12.044>.
- [70] T. Deng, X. Zhou, Porous graphite prepared by molybdenum oxide catalyzed gasification as anode material for lithium ion batteries, *Mater. Lett.* 176 (2016) 151–154, <https://doi.org/10.1016/j.matlet.2016.04.073>.
- [71] J. Billaud, F. Bouville, T. Magrini, C. Villevieille, A.R. Studart, Magnetically aligned graphite electrodes for high-rate performance Li-ion batteries, *Nat. Energy* 1 (2016) 1–6, <https://doi.org/10.1038/nenergy.2016.97>.
- [72] K.H. Chen, M.J. Namkoong, V. Goel, C. Yang, S. Kazemiabnabi, S.M. Mortuza, E. Kazyak, J. Mazunder, K. Thornton, J. Sakamoto, N.P. Dasgupta, Efficient fast-charging of lithium-ion batteries enabled by laser-patterned three-dimensional graphite anode architectures, *J. Power Sources* 471 (2020) 228475, , <https://doi.org/10.1016/j.jpowsour.2020.228475>.
- [73] W. Lu, L. Cong, Y. Liu, J. Liu, A. Mauger, C.M. Julien, L. Sun, H. Xie, Pseudocapacitance controlled fast-charging and long-life lithium ion battery achieved via a 3D mutually embedded VPO₄/rGO electrode, *J. Alloys Compd.* 812 (2020) 152135, , <https://doi.org/10.1016/j.jallcom.2019.152135>.
- [74] J. Kim, S.M. Nithya Jeghan, G. Lee, Superior fast-charging capability of graphite anode via facile surface treatment for lithium-ion batteries, *Microporous Mesoporous Mater* 305 (2020) 110325, , <https://doi.org/10.1016/j.micromeso.2020.110325>.
- [75] Q. Cheng, R. Yuge, K. Nakahara, N. Tamura, S. Miyamoto, KOH etched graphite for fast chargeable lithium-ion batteries, *J. Power Sources* 284 (2015) 258–263, <https://doi.org/10.1016/j.jpowsour.2015.03.036>.
- [76] K. Xu, Electrolytes and interphases in Li-ion batteries and beyond, *Chem. Rev.* 114 (2014) 11503–11618, <https://doi.org/10.1021/cr500003w>.
- [77] Y. Wu, W. Wang, J. Ming, M. Li, L. Xie, X. He, J. Wang, S. Liang, Y. Wu, An exploration of new energy storage system: high energy density, high safety, and fast charging lithium ion battery, *Adv. Funct. Mater.* 29 (2019) 1–7, <https://doi.org/10.1002/adfm.201805978>.
- [78] B. Ali, R. Muhammad, D.A. Anang, M. kyung Cho, J.Y. Kim, K.W. Nam, Ge-doped LiTiGeO ($x = 0.05$) as a fast-charging, long-life bi-functional anode material for lithium- and sodium-ion batteries, *Ceram. Int.* 46 (2020) 16556–16563, <https://doi.org/10.1016/j.ceramint.2020.03.223>.
- [79] J. Wang, Y. Xia, Y. Liu, W. Li, D. Zhao, Mass production of large-pore phosphorus-doped mesoporous carbon for fast-rechargeable lithium-ion batteries, *Energy Storage Mater.* 22 (2019) 147–153, <https://doi.org/10.1016/j.ensm.2019.01.008>.
- [80] K.G. Gallagher, S.E. Trask, C. Bauer, T. Woehrle, S.F. Lux, M. Tschech, P. Lamp, B.J. Polzin, S. Ha, B. Long, Q. Wu, W. Lu, D.W. Dees, A.N. Jansen, Optimizing areal capacities through understanding the limitations of lithium-ion electrodes, *J. Electrochem. Soc.* 163 (2016) A138–A149, <https://doi.org/10.1149/2.0321602jes>.
- [81] Q. Liu, C. Du, B. Shen, P. Zuo, X. Cheng, Y. Ma, G. Yin, Y. Gao, Understanding undesirable anode lithium plating issues in lithium-ion batteries, *RSC Adv.* 6 (2016) 88683–88700, <https://doi.org/10.1039/c6ra19482f>.
- [82] S.S. Zhang, K. Xu, T.R. Jow, Study of the charging process of a LiCoO₂-based Li-ion battery, *J. Power Sources* 160 (2006) 1349–1354, <https://doi.org/10.1016/j.jpowsour.2006.02.087>.
- [83] B. Anasori, M.R. Lukatskaya, Y. Gogotsi, 2D metal carbides and nitrides (MXenes) for energy storage, *Nat. Rev. Mater.* 2 (2017), <https://doi.org/10.1038/natrevmats.2016.98>.
- [84] Y. Kuang, C. Chen, D. Kirsch, L. Hu, Thick electrode batteries: principles, opportunities, and challenges, *Adv. Energy Mater.* 9 (2019) 1–19, <https://doi.org/10.1002/aenm.201901457>.
- [85] S. Yuan, X.L. Huang, D.L. Ma, H.G. Wang, F.Z. Meng, X.B. Zhang, Engraving copper foil to give large-scale binder-free porous CuO arrays for a high-performance sodium-ion battery anode, *Adv. Mater.* 26 (2014) 2273–2279, <https://doi.org/10.1002/adma.201304469>.
- [86] W. Yuan, Z. Yan, B. Pan, Z. Qiu, J. Luo, Z. Tan, Y. Tang, Z. Li, Hierarchical MCMB/CuO/Cu anode with super-hydrophilic substrate and blind-hole structures for lithium-ion batteries, *J. Alloys Compd.* 719 (2017) 353–364, <https://doi.org/10.1016/j.jallcom.2017.05.195>.
- [87] J.W. Fergus, Recent developments in cathode materials for lithium ion batteries, *J. Power Sources* 195 (2010) 939–954, <https://doi.org/10.1016/j.jpowsour.2009.08.089>.
- [88] H. Zhao, X. Gao, Y. Li, Q. Ran, C. Fu, Y. Feng, J. Liu, X. Liu, J. Su, Synergistic effects of zinc-doping and nano-rod morphology on enhancing the electrochemical properties of spinel Li-Mn-O material, *Ceram. Int.* 45 (2019) 17591–17597, <https://doi.org/10.1016/j.ceramint.2019.05.324>.
- [89] K. Zhao, M. Pharr, J.J. Vlassak, Z. Suo, K. Zhao, M. Pharr, J.J. Vlassak, Z. Suo, Fracture of electrodes in lithium-ion batteries caused by fast charging Fracture of electrodes in lithium-ion batteries caused by fast charging, 073517 (2013). 10. 1063/1.3492617.
- [90] J. Christensen, J. Newman, Stress generation and fracture in lithium insertion materials, *J. Solid State Electrochem.* 10 (2006) 293–319, <https://doi.org/10.1007/s10008-006-0095-1>.
- [91] S. Xia, L. Mu, Z. Xu, J. Wang, C. Wei, L. Liu, P. Pianetta, K. Zhao, X. Yu, F. Lin, Y. Liu, Chemomechanical interplay of layered cathode materials undergoing fast charging in lithium batteries, *Nano Energy* 53 (2018) 753–762, <https://doi.org/10.1016/j.nanoen.2018.09.051>.
- [92] A. Mukhopadhyay, B.W. Sheldon, Deformation and stress in electrode materials for Li-ion batteries, *Prog. Mater. Sci.* 63 (2014) 58–116, <https://doi.org/10.1016/j.pmatsci.2014.02.001>.
- [93] M. Wohlfahrt-Mehrens, C. Vogler, J. Garche, Aging mechanisms of lithium cathode materials, *J. Power Sources* 127 (2004) 58–64, <https://doi.org/10.1016/j.jpowsour.2003.09.034>.
- [94] H. Kim, M.G. Kim, H.Y. Jeong, H. Nam, J. Cho, A new coating method for alleviating surface degradation of LiNi_{0.6}Co_{0.2}Mn_{0.2}O₂ cathode material: nanoscale surface treatment of primary particles, *Nano Lett.* 15 (2015) 2111–2119, <https://doi.org/10.1021/acs.nanolett.5b00045>.
- [95] H. Chen, C.P. Grey, Molten salt synthesis and high rate performance of the “desert-rose” form of LiCoO₂, *Adv. Mater.* 20 (2008) 2206–2210, <https://doi.org/10.1002/adma.200702655>.
- [96] H.L. Tsai, C. Te Hsieh, J. Li, Y.A. Gandomi, Enabling high rate charge and discharge capability, low internal resistance, and excellent cycleability for Li-ion batteries utilizing graphene additives, *Electrochim. Acta* 273 (2018) 200–207, <https://doi.org/10.1016/j.electacta.2018.03.154>.
- [97] U. Nisar, R. Amin, R. Essehli, R.A. Shakoor, R. Kahraman, D.K. Kim, M.A. Khaleel, I. Belharouak, Extreme fast charging characteristics of zirconia modified LiNi_{0.5}Mn_{1.5}O₄ cathode for lithium ion batteries, *J. Power Sources* 396 (2018) 774–781, <https://doi.org/10.1016/j.jpowsour.2018.06.065>.
- [98] K. Karthikeyan, S. Amareesh, V. Aravindan, W.S. Kim, K.W. Nam, X.Q. Yang, Y.S. Lee, Li(Mn_{1/3}Ni_{1/3}Fe_{1/3})O₂: Polyaniiline hybrids as cathode active material with ultra-fast charge-discharge capability for lithium batteries, *J. Power Sources* 232 (2013) 240–245, <https://doi.org/10.1016/j.jpowsour.2012.12.114>.
- [99] F. Zoller, D. Böhm, J. Luxa, M. Döblinger, Z. Sofer, D. Semenenko, T. Bein, D. Fattakhova-Rohlfing, Freestanding LiFe_{0.2}Mn_{0.8}PO₄/rGO nanocomposites as high energy density fast charging cathodes for lithium-ion batteries, *Mater. Today Energy* 16 (2020), <https://doi.org/10.1016/j.mtener.2020.100416>.
- [100] W. Wen, S. Chen, Y. Fu, X. Wang, H. Shu, A core-shell structure spinel cathode material with a concentration-gradient shell for high performance lithium-ion batteries, *J. Power Sources* 274 (2015) 219–228, <https://doi.org/10.1016/j.jpowsour.2014.10.027>.
- [101] Y. Jiang, Z. Liu, Y. Zhang, H. Hu, X. Teng, D. Wang, P. Gao, Y. Zhu, Full-gradient structured LiNi_{0.8}Co_{0.1}Mn_{0.1}O₂ cathode material with improved rate and cycle performance for lithium ion batteries, *Electrochim. Acta* 309 (2019) 74–85, <https://doi.org/10.1016/j.electacta.2019.04.058>.
- [102] Q. Ran, H. Zhao, Q. Wang, X. Shu, Y. Hu, S. Hao, M. Wang, J. Liu, M. Zhang, H. Li, N. Liu, X. Liu, Dual functions of gradient phosphate polyanion doping on improving the electrochemical performance of Ni-rich LiNi_{0.6}Co_{0.2}Mn_{0.2}O₂ cathode at high cut-off voltage and high temperature, *Electrochim. Acta* 299 (2019) 971–978, <https://doi.org/10.1016/j.electacta.2019.01.082>.
- [103] M. Zhang, M. Tan, H. Zhao, S. Liu, X. Shu, Y. Hu, J. Liu, Q. Ran, H. Li, X. Liu, Enhanced high-voltage cycling stability and rate capability of magnesium and titanium co-doped lithium cobalt oxides for lithium-ion batteries, *Appl. Surf. Sci.* 458 (2018) 111–118, <https://doi.org/10.1016/j.apsusc.2018.07.091>.
- [104] K. Hatakeyama-Sato, T. Akahane, C. Go, T. Kaseyama, T. Yoshimoto, K. Oyaizu, Ultrafast charge/discharge by a 99.9% conventional lithium iron phosphate electrode containing 0.1% redox-active fluorin polymer, *ACS Energy Lett.* (2020) 0–19, <https://doi.org/10.1021/acsenergylett.0c00622>.
- [105] A. Lee, M. Vörös, W.M. Dose, J. Niklas, O. Poluektov, R.D. Schaller, H. Iddir, V.A. Maroni, E. Lee, B. Ingram, L.A. Curtiss, C.S. Johnson, Photo-accelerated fast charging of lithium-ion batteries, *Nat. Commun.* (2019) 1–7, <https://doi.org/10.1038/s41567-019-0527-0>.

- 1038/s41467-019-12863-6 (n.d.).
- [106] A.M. Colclasure, A.R. Dunlop, S.E. Trask, B.J. Polzin, A.N. Jansen, K. Smith, Requirements for enabling extreme fast charging of high energy density Li-ion cells while avoiding lithium plating, *J. Electrochem. Soc.* 166 (2019) A1412–A1424, <https://doi.org/10.1149/2.0451908jes>.
- [107] A. Friesen, X. Mönnighoff, M. Börner, J. Haetge, F.M. Schappacher, M. Winter, Influence of temperature on the aging behavior of 18650-type lithium ion cells: a comprehensive approach combining electrochemical characterization and post-mortem analysis, *J. Power Sources* 342 (2017) 88–97, <https://doi.org/10.1016/j.jpowsour.2016.12.040>.
- [108] M. Börner, A. Friesen, M. Grützke, Y.P. Stenzel, G. Brunklaus, J. Haetge, S. Nowak, F.M. Schappacher, M. Winter, Correlation of aging and thermal stability of commercial 18650-type lithium ion batteries, *J. Power Sources* 342 (2017) 382–392, <https://doi.org/10.1016/j.jpowsour.2016.12.041>.
- [109] E.R. Logan, J.R. Dahn, Electrolyte Design for Fast-Charging Li-Ion Batteries, *Trends Chem.* 2 (2020) 354–366, <https://doi.org/10.1016/j.trechm.2020.01.011>.
- [110] J.G. Han, M.Y. Jeong, K. Kim, C. Park, C.H. Sung, D.W. Bak, K.H. Kim, K.M. Jeong, N.S. Choi, An electrolyte additive capable of scavenging HF and PF₅ enables fast charging of lithium-ion batteries in LiPF₆-based electrolytes, *J. Power Sources* 446 (2020) 227366, , <https://doi.org/10.1016/j.jpowsour.2019.227366>.
- [111] J. Zheng, M.H. Engelhard, D. Mei, S. Jiao, B.J. Polzin, J.G. Zhang, W. Xu, Electrolyte additive enabled fast charging and stable cycling lithium metal batteries, *Nat. Energy* 2 (2017), <https://doi.org/10.1038/nenergy.2017.12>.
- [112] X. Zhang, Q. Wu, X. Guan, F. Cao, C. Li, J. Xu, Lithium dendrite-free and fast-charging for high voltage nickel-rich lithium metal batteries enabled by bifunctional sulfone-containing electrolyte additives, *J. Power Sources* 452 (2020) 227833, , <https://doi.org/10.1016/j.jpowsour.2020.227833>.
- [113] W. Zhao, F. Ren, Q. Yan, H. Liu, Y. Yang, A facile synthesis of non-aqueous LiPO₂F₂ solution as the electrolyte additive for high performance lithium ion batteries, *Chin. Chem. Lett.* (2020) 4–7, <https://doi.org/10.1016/j.ccl.2020.05.006>.
- [114] J. Shi, N. Ehteshami, J. Ma, H. Zhang, H. Liu, X. Zhang, J. Li, E. Paillard, Improving the graphite/electrolyte interface in lithium-ion battery for fast charging and low temperature operation: fluorosulfonyl isocyanate as electrolyte additive, *J. Power Sources* 429 (2019) 67–74, <https://doi.org/10.1016/j.jpowsour.2019.04.113>.
- [115] Q.Q. Liu, R. Petibon, C.Y. Du, J.R. Dahn, Effects of electrolyte additives and solvents on unwanted lithium plating in lithium-ion cells, *J. Electrochem. Soc.* 164 (2017) A1173–A1183, <https://doi.org/10.1149/2.1081706jes>.
- [116] E.R. Logan, E.M. Tonita, K.L. Gering, J.I. Li, X. Ma, L.Y. Beaulieu, J.R. Dahn, A study of the physical properties of Li-ion battery electrolytes containing esters, *J. Electrochem. Soc.* 165 (2018) A21–A30, <https://doi.org/10.1149/2.0271802jes>.
- [117] S. Jurng, S. Park, T. Yoon, H. Kim, H. Jeong, J.H. Ryu, J.J. Kim, S.M. Oh, Low-temperature performance improvement of graphite electrode by allyl sulfide additive and its film-forming mechanism, *J. Electrochem. Soc.* 163 (2016) A1798–A1804, <https://doi.org/10.1149/2.0051609jes>.
- [118] Y. Yamada, A. Yamada, Review—superconcentrated electrolytes for lithium batteries, *J. Electrochem. Soc.* 162 (2015) A2406–A2423, <https://doi.org/10.1149/2.0041514jes>.
- [119] M. Okoshi, C.P. Chou, H. Nakai, Theoretical analysis of carrier ion diffusion in superconcentrated electrolyte solutions for sodium-ion batteries, *J. Phys. Chem. B* 122 (2018) 2600–2609, <https://doi.org/10.1021/acs.jpcb.7b10589>.
- [120] Y. Yamada, M. Yaegashi, T. Abe, A. Yamada, A superconcentrated ether electrolyte for fast-charging Li-ion batteries, *Chem. Commun.* 49 (2013) 11194–11196, <https://doi.org/10.1039/c3cc46656c>.
- [121] Y. Yamada, K. Furukawa, K. Sodeyama, K. Kikuchi, M. Yaegashi, Y. Tateyama, A. Yamada, Unusual stability of acetonitrile-based superconcentrated electrolytes for fast-charging lithium-ion batteries, *J. Am. Chem. Soc.* 136 (2014) 5039–5046, <https://doi.org/10.1021/ja412807w>.
- [122] K.M. Diederichsen, E.J. McShane, B.D. McCloskey, Promising routes to a high Li⁺ transference number electrolyte for lithium ion batteries, *ACS Energy Lett.* 2 (2017) 2563–2575, <https://doi.org/10.1021/acsenergylett.7b00792>.
- [123] H.G. Buss, S.Y. Chan, N.A. Lynd, B.D. McCloskey, Nonaqueous polyelectrolyte solutions as liquid electrolytes with high lithium ion transference number and conductivity, *ACS Energy Lett.* 2 (2017) 481–487, <https://doi.org/10.1021/acsenergylett.6b00724>.
- [124] J. Popovic, D. Höfler, J.P. Melchior, A. Münchinger, B. List, J. Maier, High Lithium Transference number electrolytes containing tetratriylpropene's lithium salt, *J. Phys. Chem. Lett.* 9 (2018) 5116–5120, <https://doi.org/10.1021/acs.jpclett.8b01846>.
- [125] D.S. Hall, A. Eldesoky, E.R. Logan, E.M. Tonita, X. Ma, J.R. Dahn, Exploring classes of co-solvents for fast-charging lithium-ion cells, *J. Electrochem. Soc.* 165 (2018) A2365–A2373, <https://doi.org/10.1149/2.1351810jes>.
- [126] X. Wu, T. Liu, Y. Bai, X. Feng, M.M. Rahman, C.J. Sun, F. Lin, K. Zhao, Z. Du, Effects of solvent formulations in electrolytes on fast charging of Li-ion cells, *Electrochim. Acta* 353 (2020) 136453, , <https://doi.org/10.1016/j.electacta.2020.136453>.
- [127] Z. Du, D.L. Wood, I. Belharouak, Enabling fast charging of high energy density Li-ion cells with high lithium ion transport electrolytes, *Electrochem. Commun.* 103 (2019) 109–113, <https://doi.org/10.1016/j.elecom.2019.04.013>.
- [128] M.C. Smart, B.V. Ratnakumar, S. Surampudi, Use of organic esters as cosolvents in electrolytes for lithium-ion batteries with improved low temperature performance, *J. Electrochem. Soc.* 149 (2002) A361, <https://doi.org/10.1149/1.1453407>.
- [129] X. Ma, J. Li, S.L. Glazier, L. Ma, K.L. Gering, J.R. Dahn, A study of highly conductive ester co-solvents in Li[Ni_{0.8}Mn_{0.3}Co_{0.2}]O₂/Graphite pouch cells, *Electrochim. Acta* 270 (2018) 215–223, <https://doi.org/10.1016/j.electacta.2018.03.006>.
- [130] P. Hilbig, L. Ibing, M. Winter, I. Cekic-Laskovic, Butyronitrile-based electrolytes for fast charging of lithium-ion batteries, *Energies* 12 (2019), <https://doi.org/10.3390/en12152869>.
- [131] C. Heubner, M. Schneider, C. Lämmel, A. Michaelis, Local heat generation in a single stack lithium ion battery cell, *Electrochim. Acta* 186 (2015) 404–412, <https://doi.org/10.1016/j.electacta.2015.10.182>.
- [132] 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>.
- [133] T.M. Bandhauer, S. Garimella, T.F. Fuller, A critical review of thermal issues in lithium-ion batteries, *J. Electrochim. Soc.* 158 (2011) R1, <https://doi.org/10.1149/1.3515880>.
- [134] Y. Ye, L.H. Saw, Y. Shi, K. Somasundaram, A.A.O. Tay, Effect of thermal contact resistances on fast charging of large format lithium ion batteries, *Electrochim. Acta* 134 (2014) 327–337, <https://doi.org/10.1016/j.electacta.2014.04.134>.
- [135] L.H.J. Raijmakers, D.L. Danilov, R.A. Eichel, P.H.L. Notten, A review on various temperature-indication methods for Li-ion batteries, *Appl. Energy* 240 (2019) 918–945, <https://doi.org/10.1016/j.apenergy.2019.02.078>.
- [136] K.A. Murashko, A.V. Mityakov, V.Y. Mityakov, S.Z. Sapozhnikov, J. Jokiniemi, J. Pyrhönen, Determination of the entropy change profile of a cylindrical lithium-ion battery by heat flux measurements, *J. Power Sources* 330 (2016) 61–69, <https://doi.org/10.1016/j.jpowsour.2016.08.130>.
- [137] E. Schuster, C. Ziebert, A. Melcher, M. Rohde, H.J. Seifert, Thermal behavior and electrochemical heat generation in a commercial 40 Ah lithium ion pouch cell, *J. Power Sources* 286 (2015) 580–589, <https://doi.org/10.1016/j.jpowsour.2015.03.170>.
- [138] J. Vetter, P. Novák, M.R. Wagner, C. Veit, K.C. Möller, J.O. Besenhard, M. Winter, M. Wohlfahrt-Mehrens, C. Vogler, A. Hammouche, Ageing mechanisms in lithium-ion batteries, *J. Power Sources* 147 (2005) 269–281, <https://doi.org/10.1016/j.jpowsour.2005.01.006>.
- [139] A.M. Andersson, K. Edström, Chemical composition and morphology of the elevated temperature SEI on graphite, *J. Electrochim. Soc.* 148 (2001) A1100, <https://doi.org/10.1149/1.1397771>.
- [140] S.S. Zhang, K. Xu, T.R. Jow, Optimization of the forming conditions of the solid-state interface in the Li-ion batteries, *J. Power Sources* 130 (2004) 281–285, <https://doi.org/10.1016/j.jpowsour.2003.12.012>.
- [141] N. Yuca, H. Zhao, X. Song, M.F. Dogdu, W. Yuan, Y. Fu, V.S. Battaglia, X. Xiao, G. Liu, A systematic investigation of polymer binder flexibility on the electrode performance of lithium-ion batteries, *ACS Appl. Mater. Interfaces* 6 (2014) 17111–17118, <https://doi.org/10.1021/am504736y>.
- [142] C.R. Birk, M.R. Roberts, E. McTurk, P.G. Bruce, D.A. Howey, Degradation diagnostics for lithium ion cells, *J. Power Sources* 341 (2017) 373–386, <https://doi.org/10.1016/j.jpowsour.2016.12.011>.
- [143] T.R. Tanim, E.J. Dufek, L.K. Walker, C.D. Ho, C.E. Hendricks, J.P. Christoffersen, Advanced diagnostics to evaluate heterogeneity in lithium-ion battery modules, *ETransportation* 3 (2020) 100045, , <https://doi.org/10.1016/j.etrans.2020.100045>.
- [144] W. Song, M. Chen, F. Bai, S. Lin, Y. Chen, Z. Feng, Non-uniform effect on the thermal/aging performance of Lithium-ion pouch battery, *Appl. Therm. Eng.* 128 (2018) 1165–1174, <https://doi.org/10.1016/j.applthermaleng.2017.09.090>.
- [145] X. Feng, D. Ren, X. He, M. Ouyang, Mitigating thermal runaway of lithium-ion batteries, *Joule* (2020) 1–28, <https://doi.org/10.1016/j.joule.2020.02.010>.
- [146] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, X. He, Thermal runaway mechanism of lithium ion battery for electric vehicles: a review, *Energy Storage Mater* 10 (2018) 246–267, <https://doi.org/10.1016/j.ensmat.2017.05.013>.
- [147] Y. Li, X. Feng, D. Ren, et al., Varying thermal runaway mechanism caused by fast charging for high energy pouch batteries, *Electrochim. Soc.* (6) (2019) 585–585.
- [148] Z. Chen, P.C. Hsu, J. Lopez, Y. Li, J.W.F. To, N. Liu, C. Wang, S.C. Andrews, J. Liu, Y. Cui, Z. Bao, Fast and reversible thermoresponsive polymer switching materials for safer batteries, *Nat. Energy* 1 (2016), <https://doi.org/10.1038/nenergy.2016.9>.
- [149] K. Liu, Y. Liu, D. Lin, A. Pei, Y. Cui, Materials for lithium-ion battery safety, *Sci. Adv.* 4 (2018), <https://doi.org/10.1126/sciadv.aas9820>.
- [150] Y. Li, X. Liu, D. Ren, H. Hsu, G.L. Xu, J. Hou, L. Wang, X. Feng, L. Lu, W. Xu, Y. Ren, R. Li, X. He, K. Amine, M. Ouyang, Toward a high-voltage fast-charging pouch cell with TiO₂ cathode coating and enhanced battery safety, *Nano Energy* 71 (2020) 104643, , <https://doi.org/10.1016/j.nanoen.2020.104643>.
- [151] N. Schweikert, A. Hofmann, M. Schulz, M. Scheuermann, S.T. Boles, T. Hanemann, H. Hahn, S. Indris, Suppressed lithium dendrite growth in lithium batteries using ionic liquid electrolytes: investigation by electrochemical impedance spectroscopy, scanning electron microscopy, and in situ ⁷Li nuclear magnetic resonance spectroscopy, *J. Power Sources* 228 (2013) 237–243, <https://doi.org/10.1016/j.jpowsour.2012.11.124>.
- [152] M. Xu, R. Wang, P. Zhao, X. Wang, Fast charging optimization for lithium-ion batteries based on dynamic programming algorithm and electrochemical-thermal-capacity fad coupled model, *J. Power Sources* 438 (2019) 227015, , <https://doi.org/10.1016/j.jpowsour.2019.227015>.
- [153] Z. Chu, X. Feng, L. Lu, J. Li, X. Han, M. Ouyang, Non-destructive fast charging algorithm of lithium-ion batteries based on the control-oriented electrochemical model, *Appl. Energy* 204 (2017) 1240–1250, <https://doi.org/10.1016/j.apenergy.2017.03.111>.
- [154] M. Song, S.Y. Choe, Fast and safe charging method suppressing side reaction and lithium deposition reaction in lithium ion battery, *J. Power Sources* 436 (2019) 226835, , <https://doi.org/10.1016/j.jpowsour.2019.226835>.
- [155] G. Zhu, K. Wen, W. Lv, X. Zhou, Y. Liang, F. Yang, Z. Chen, M. Zou, J. Li, Y. Zhang, W. He, Materials insights into low-temperature performances of lithium-ion

- batteries, *J. Power Sources* 300 (2015) 29–40, <https://doi.org/10.1016/j.jpowsour.2015.09.056>.
- [156] G. Trentadue, A. Lucas, M. Otura, K. Plakostathis, M. Zanni, H. Scholz, *Extreme Temp.* (2018) 1–13, <https://doi.org/10.3390/en11081937>.
- [157] X.G. Yang, C.Y. Wang, Understanding the trilemma of fast charging, energy density and cycle life of lithium-ion batteries, *J. Power Sources* 402 (2018) 489–498, <https://doi.org/10.1016/j.jpowsour.2018.09.069>.
- [158] M. Ecker, P. Shafei Sabet, D.U. Sauer, Influence of operational condition on lithium plating for commercial lithium-ion batteries – electrochemical experiments and post-mortem-analysis, *Appl. Energy* 206 (2017) 934–946, <https://doi.org/10.1016/j.apenergy.2017.08.034>.
- [159] A.N. Jansen, D.W. Dees, D.P. Abraham, K. Amine, G.L. Henriksen, Low-temperature study of lithium-ion cells using a Li_ySn micro-decoration electrode, *J. Power Sources* 174 (2007) 373–379, <https://doi.org/10.1016/j.jpowsour.2007.06.235>.
- [160] M.C. Smart, B.V. Ratnakumar, L.D. Whitanack, K.B. Chin, S. Surampudi, H. Croft, D. Tice, R. Staniewicz, Improved low-temperature performance of lithium-ion cells with quaternary carbonate-based electrolytes, *J. Power Sources* 119–121 (2003) 349–358, [https://doi.org/10.1016/S0378-7753\(03\)00154-X](https://doi.org/10.1016/S0378-7753(03)00154-X).
- [161] Y. Ji, Y. Zhang, C.-Y. Wang, Li-ion cell operation at low temperatures, *J. Electrochem. Soc.* 160 (2013) A636–A649, <https://doi.org/10.1149/2.047304jes>.
- [162] M.F. Hasan, C.F. Chen, C.E. Shaffer, P.P. Mukherjee, Analysis of the implications of rapid charging on lithium-ion battery performance, *J. Electrochem. Soc.* 162 (2015) A1382–A1395, <https://doi.org/10.1149/2.0871507jes>.
- [163] B.S. Vishnugopi, A. Verma, P.P. Mukherjee, Fast charging of lithium-ion batteries via electrode engineering, *J. Electrochem. Soc.* 167 (2020) 090508, , <https://doi.org/10.1149/1945-7111/ab7fb9>.
- [164] X. Hu, Y. Zheng, D.A. Howey, H. Perez, A. Foley, M. Pecht, Battery warm-up methodologies at subzero temperatures for automotive applications: recent advances and perspectives, *Prog. Energy Combust. Sci.* 77 (2020), <https://doi.org/10.1016/j.pecs.2019.100806>.
- [165] S. Wu, R. Xiong, H. Li, V. Nian, S. Ma, The state of the art on preheating lithium-ion batteries in cold weather, *J. Energy Storage* 27 (2020) 101059, , <https://doi.org/10.1016/j.est.2019.101059>.
- [166] C.-Y. Wang, T. Xu, S. Ge, G. Zhang, X.-G. Yang, Y. Ji, A fast rechargeable lithium-ion battery at subfreezing temperatures, *J. Electrochem. Soc.* 163 (2016) A1944–A1950, <https://doi.org/10.1149/2.0681609jes>.
- [167] X.G. Yang, G. Zhang, S. Ge, C.Y. Wang, Fast charging of lithium-ion batteries at all temperatures, *Proc. Natl. Acad. Sci. U. S. A.* 115 (2018) 7266–7271, <https://doi.org/10.1073/pnas.18077111515>.
- [168] C.Y. Wang, G. Zhang, S. Ge, T. Xu, Y. Ji, X.G. Yang, Y. Leng, Lithium-ion battery structure that self-heats at low temperatures, *Nature* 529 (2016) 515–518, <https://doi.org/10.1038/nature16502>.
- [169] X.G. Yang, T. Liu, Y. Gao, S. Ge, Y. Leng, D. Wang, C.Y. Wang, Asymmetric temperature modulation for extreme fast charging of lithium-ion batteries, *Joule* 3 (2019) 3002–3019, <https://doi.org/10.1016/j.joule.2019.09.021>.
- [170] C. Tian, F. Lin, M.M. Doeff, Electrochemical characteristics of layered transition metal oxide cathode materials for lithium ion batteries: surface, bulk behavior, and thermal properties, *Acc. Chem. Res.* 51 (2018) 89–96, <https://doi.org/10.1021/acs.accounts.7b00520>.
- [171] D. Anseán, M. González, J.C. Viera, V.M. García, C. Blanco, M. Valledor, Fast charging technique for high power lithium iron phosphate batteries: a cycle life analysis, *J. Power Sources* 239 (2013) 9–15, <https://doi.org/10.1016/j.jpowsour.2013.03.044>.
- [172] P.H.L. Notten, J.H.G.O.H. Veld, J.R.G. Van Beek, Boostcharging Li-ion batteries: a challenging new charging concept, *J. Power Sources* 145 (2005) 89–94, <https://doi.org/10.1016/j.jpowsour.2004.12.038>.
- [173] S.S. Zhang, The effect of the charging protocol on the cycle life of a Li-ion battery, *J. Power Sources.* 161 (2006) 1385–1391, <https://doi.org/10.1016/j.jpowsour.2006.06.040>.
- [174] A. Aryanfar, D. Brooks, B.V. Merinov, W.A. Goddard, A.J. Colussi, M.R. Hoffmann, Dynamics of lithium dendrite growth and inhibition: pulse charging experiments and monte carlo calculations, *J. Phys. Chem. Lett.* 5 (2014) 1721–1726, <https://doi.org/10.1021/jz500207a>.
- [175] F. Savoye, P. Venet, S. Pelissier, M. Millet, J. Groot, Impact of periodic current pulses on Li-ion batteries lifetime in vehicular application, *Int. J. Electr. Hybrid Veh.* 7 (2015) 323–341, <https://doi.org/10.1504/IJEHV.2015.074670>.
- [176] H.Z.Z. Beh, G.A. Covic, J.T. Boys, Effects of pulse and DC charging on lithium iron phosphate (LiFePO₄) batteries, 2013 IEEE Energy Convers. Congr. Expo. ECCE 2013, 2013, pp. 315–320, , <https://doi.org/10.1109/ECCE.2013.6646717>.
- [177] M. Petzl, M.A. Danzer, Nondestructive detection, characterization, and quantification of lithium plating in commercial lithium-ion batteries, *J. Power Sources* 254 (2014) 80–87, <https://doi.org/10.1016/j.jpowsour.2013.12.060>.
- [178] T.T. Vo, X. Chen, W. Shen, A. Kapoor, New charging strategy for lithium-ion batteries based on the integration of Taguchi method and state of charge estimation, *J. Power Sources* 273 (2015) 413–422, <https://doi.org/10.1016/j.jpowsour.2014.09.108>.
- [179] G. Sikha, P. Ramadass, B.S. Haran, R.E. White, B.N. Popov, Comparison of the capacity fade of Sony US 18650 cells charged with different protocols, *J. Power Sources* 122 (2003) 67–76, [https://doi.org/10.1016/S0378-7753\(03\)00027-2](https://doi.org/10.1016/S0378-7753(03)00027-2).
- [180] M. Abdel-Moneim, K. Trad, N. Omar, O. Hegazy, P. Van den Bossche, J. Van Mierlo, Influence analysis of static and dynamic fast-charging current profiles on ageing performance of commercial lithium-ion batteries, *Energy* 120 (2017) 179–191, <https://doi.org/10.1016/j.energy.2016.12.110>.
- [181] B. Bitzer, A. Gruhle, A new method for detecting lithium plating by measuring the cell thickness, *J. Power Sources* 262 (2014) 297–302, <https://doi.org/10.1016/j.jpowsour.2014.03.142>.
- [182] B. Lu, Y. Song, J. Zhang, Selection of charge methods for lithium ion batteries by considering diffusion induced stress and charge time, 320 (2016) 104–110. 10. 1016/j.jpowsour.2016.04.079.
- [183] F.B. Spingler, W. Wittmann, J. Sturm, B. Rieger, A. Jossen, Optimum fast charging of lithium-ion pouch cells based on local volume expansion criteria, *J. Power Sources* 393 (2018) 152–160, <https://doi.org/10.1016/j.jpowsour.2018.04.095>.
- [184] B. Rieger, S. Schlueter, S.V. Erhard, J. Schmalz, G. Reinhart, A. Jossen, Multi-scale investigation of thickness changes in a commercial pouch type lithium-ion battery, *J. Energy Storage* 6 (2016) 213–221, <https://doi.org/10.1016/j.est.2016.01.006>.
- [185] J. Sturm, F.B. Spingler, B. Rieger, A. Rheinfeld, A. Jossen, Non-destructive detection of local aging in lithium-ion pouch cells by multi-directional laser scanning, *J. Electrochem. Soc.* 164 (2017) A1342–A1351, <https://doi.org/10.1149/2.0161707jes>.
- [186] S. Schindler, M. Bauer, H. Cheetamun, M.A. Danzer, Fast charging of lithium-ion cells : identification of aging-minimal current profile using a design of experiment approach and a mechanistic degradation analysis, *J. Energy Storage* 19 (2018) 364–378, <https://doi.org/10.1016/j.est.2018.08.002>.
- [187] I.D. Campbell, K. Gopalakrishnan, M. Marinescu, M. Torchio, G.J. Offer, D. Raimondo, Optimising lithium-ion cell design for plug-in hybrid and battery electric vehicles, *J. Energy Storage* 22 (2019) 228–238, <https://doi.org/10.1016/j.est.2019.01.006>.
- [188] D. Grazioli, M. Magri, A. Salvadori, Computational modeling of Li-ion batteries, *Comput. Mech.* 58 (2016) 889–909, <https://doi.org/10.1007/s00466-016-1325-8>.
- [189] S. Santhanagopalan, Q. Guo, P. Ramadass, R.E. White, Review of models for predicting the cycling performance of lithium ion batteries, *J. Power Sources* 156 (2006) 620–628, <https://doi.org/10.1016/j.jpowsour.2005.05.070>.
- [190] A. Jokar, B. Rajabloo, M. Désilets, M. Lacroix, Review of simplified pseudo-two-dimensional models of lithium-ion batteries, *J. Power Sources*. 327 (2016) 44–55, <https://doi.org/10.1016/j.jpowsour.2016.07.036>.
- [191] J. Liu, Q. Duan, H. Chen, J. Sun, Q. Wang, An optimal multistage charge strategy for commercial lithium ion batteries, *Sustain. Energy Fuels* 2 (2018) 1726–1736, <https://doi.org/10.1039/c8se00235e>.
- [192] C. Zou, X. Hu, Z. Wei, X. Tang, Electrothermal dynamics-conscious lithium-ion battery cell-level charging management via state-monitored predictive control, *Energy* 141 (2017) 250–259, <https://doi.org/10.1016/j.energy.2017.09.048>.
- [193] Z. Guo, B.Y. Liaw, X. Qiu, L. Gao, C. Zhang, Optimal charging method for lithium ion batteries using a universal voltage protocol accommodating aging, *J. Power Sources* 274 (2015) 957–964, <https://doi.org/10.1016/j.jpowsour.2014.10.185>.
- [194] M. Ye, H. Gong, R. Xiong, H. Mu, Research on the battery charging strategy with charging and temperature rising control awareness, *IEEE Access* 6 (2018) 64193–64201, <https://doi.org/10.1109/ACCESS.2018.2876359>.
- [195] X. Wu, W. Shi, J. Du, Multi-objective optimal charging method for lithium-ion batteries, *Energies* 10 (2017) 1–18, <https://doi.org/10.3390/en10091271>.
- [196] L. Patnaik, A.V.J.S. Praneeth, S.S. Williamson, A closed-loop constant-temperature constant-voltage charging technique to reduce charge time of lithium-ion batteries, *IEEE Trans. Ind. Electron.* 66 (2019) 1059–1067, <https://doi.org/10.1109/TIE.2018.2833038>.
- [197] H.E. Perez, X. Hu, S. Dey, S.J. Moura, Optimal charging of Li-ion batteries with coupled electro-thermal-aging dynamics, *IEEE Trans. Veh. Technol.* 66 (2017) 7761–7770, <https://doi.org/10.1109/TVT.2017.2676044>.
- [198] H. Min, W. Sun, X. Li, D. Guo, Y. Yu, T. Zhu, Z. Zhao, Research on the optimal charging strategy for Li-ion batteries based on multi-objective optimization, *Energies*. 10 (2017) 1–15, <https://doi.org/10.3390/en10050709>.
- [199] X. Hu, Y. Zheng, X. Lin, Y. Xie, Optimal multistage charging of NCA/graphite lithium-ion batteries based on electro-thermal-aging dynamics, *IEEE Trans. Transp. Electrif.* (2020) 7782, <https://doi.org/10.1109/TTE.2020.2977092>.
- [200] C. Zhang, J. Jiang, Y. Gao, W. Zhang, Q. Liu, X. Hu, Charging optimization in lithium-ion batteries based on temperature rise and charge time, *Appl. Energy* 194 (2017) 569–577, <https://doi.org/10.1016/j.apenergy.2016.10.059>.
- [201] M. Khamar, J. Askari, A charging method for Lithium-ion battery using min-max optimal control, 22nd Iran. Conf. Electr. Eng. ICEE 2014. 2014, pp. 1239–1243, , <https://doi.org/10.1109/IranianCEE.2014.6999724>.
- [202] X. Hu, S. Li, H. Peng, F. Sun, Charging time and loss optimization for LiNMC and LiFePO₄ batteries based on equivalent circuit models, *J. Power Sources*. 239 (2013) 449–457, <https://doi.org/10.1016/j.jpowsour.2013.03.157>.
- [203] C. Zou, X. Hu, Z. Wei, T. Wik, B. Egardt, Electrochemical estimation and control for lithium-ion battery health-aware fast charging, *IEEE Trans. Ind. Electron.* 65 (2018) 6635–6645, <https://doi.org/10.1109/TIE.2017.2772154>.
- [204] M. Xu, R. Wang, B. Reichman, X. Wang, Modeling the effect of two-stage fast charging protocol on thermal behavior and charging energy efficiency of lithium-ion batteries, *J. Energy Storage* 20 (2018) 298–309, <https://doi.org/10.1016/j.est.2018.09.004>.
- [205] M. Xu, R. Wang, P. Zhao, X. Wang, Fast charging optimization for lithium-ion batteries based on dynamic programming algorithm and electrochemical-thermal-capacity fade coupled model, *J. Power Sources* 438 (2019) 227015, , <https://doi.org/10.1016/j.jpowsour.2019.227015>.
- [206] C. Zou, C. Manzie, D. Nesic, PDE battery model simplification for charging strategy evaluation, 2015 10th Asian Control Conf. Emerg. Control Tech. A Sustain. World, ASCC 2015, 2015, <https://doi.org/10.1109/ASCC.2015.7244553>.
- [207] W. Waag, C. Fleischer, D.U. Sauer, Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles, *J. Power Sources* 258 (2014) 321–339, <https://doi.org/10.1016/j.jpowsour.2014.02.064>.
- [208] A. Rodríguez, G.L. Plett, M.S. Trimble, Comparing four model-order reduction techniques, applied to lithium-ion battery-cell internal electrochemical transfer functions, *ETransportation* 1 (2019) 100009, , <https://doi.org/10.1016/j.etran.2019.100009>.

- [209] D. Zhang, B.N. Popov, R.E. White, Modeling lithium intercalation of a single spinel particle under potentiodynamic control, *J. Electrochem. Soc.* 147 (2000) 831, <https://doi.org/10.1149/1.1393279>.
- [210] T.R. Tanim, C.D. Rahn, C.Y. Wang, A temperature dependent, single particle, lithium ion cell model including electrolyte diffusion, *J. Dyn. Syst. Meas. Control. Trans. ASME.* 137 (2015) 1–11, <https://doi.org/10.1115/1.4028154>.
- [211] X. Han, M. Ouyang, L. Lu, J. Li, Simplification of physics-based electrochemical model for lithium ion battery on electric vehicle. Part I: Diffusion simplification and single particle model, *J. Power Sources* 278 (2015) 802–813, <https://doi.org/10.1016/j.jpowsour.2014.12.101>.
- [212] E. Prada, D. Di Domenico, Y. Creff, J. Bernard, V. Sauvant-Moynot, F. Huet, Simplified electrochemical and thermal model of LiFePO₄-graphite Li-ion batteries for fast charge applications, *J. Electrochem. Soc.* 159 (2012) A1508–A1519, <https://doi.org/10.1149/2.064209jes>.
- [213] M. Vasilyeva, A. Mistry, P.P. Mukherjee, Multiscale model reduction for pore-scale simulation of Li-ion batteries using GMsFEM, *J. Comput. Appl. Math.* 344 (2018) 73–88, <https://doi.org/10.1016/j.cam.2018.05.016>.
- [214] J. Marcicki, M. Canova, A.T. Conlisk, G. Rizzoni, Design and parametrization analysis of a reduced-order electrochemical model of graphite/LiFePO₄ cells for SOC/SOH estimation, *J. Power Sources.* 237 (2013) 310–324, <https://doi.org/10.1016/j.jpowsour.2012.12.120>.
- [215] M.M. Majdabadi, S. Farhad, M. Farkhondeh, R.A. Fraser, M. Fowler, Simplified electrochemical multi-particle model for LiFePO₄ cathodes in lithium-ion batteries, *J. Power Sources* 275 (2015) 633–643, <https://doi.org/10.1016/j.jpowsour.2014.11.066>.
- [216] X. Han, M. Ouyang, L. Lu, J. Li, Simplification of physics-based electrochemical model for lithium ion battery on electric vehicle. Part II: Pseudo-two-dimensional model simplification and state of charge estimation, *J. Power Sources.* 278 (2015) 814–825, <https://doi.org/10.1016/j.jpowsour.2014.08.089>.
- [217] S.Y. Choe, X. Li, M. Xiao, Fast charging method based on estimation of ion concentrations using a reduced order of electrochemical thermal model for lithium ion polymer battery, *World Electr. Veh. J.* 6 (2013) 782–792, <https://doi.org/10.3390/wevj6030782>.
- [218] S. Pramanik, S. Anwar, Electrochemical model based charge optimization for lithium-ion batteries, *J. Power Sources* 313 (2016) 164–177, <https://doi.org/10.1016/j.jpowsour.2016.01.096>.
- [219] J. Sieg, J. Bandlow, T. Mitsch, D. Dragicevic, T. Materna, B. Spier, H. Witzenhausen, M. Eckert, D.U. Sauer, Fast charging of an electric vehicle lithium-ion battery at the limit of the lithium deposition process, *J. Power Sources* 427 (2019) 260–270, <https://doi.org/10.1016/j.jpowsour.2019.04.047>.
- [220] F. Ringbeck, M. Garbade, D.U. Sauer, Uncertainty-aware state estimation for electrochemical model-based fast charging control of lithium-ion batteries, *J. Power Sources* 470 (2020) 228221, , <https://doi.org/10.1016/j.jpowsour.2020.228221>.
- [221] Y. Yin, Y. Hu, S.Y. Choe, H. Cho, W.T. Joe, New fast charging method of lithium-ion batteries based on a reduced order electrochemical model considering side reaction, *J. Power Sources* 423 (2019) 367–379, <https://doi.org/10.1016/j.jpowsour.2019.03.007>.
- [222] S. Tippmann, D. Walper, L. Balboa, B. Spier, W.G. Bessler, Low-temperature charging of lithium-ion cells Part I: Electrochemical modeling and experimental investigation of degradation behavior, *J. Power Sources* 252 (2014) 305–316, <https://doi.org/10.1016/j.jpowsour.2013.12.022>.
- [223] J. Remmlinger, S. Tippmann, M. Buchholz, K. Dietmayer, Low-temperature charging of lithium-ion cells Part II: Model reduction and application, *J. Power Sources* 254 (2014) 268–276, <https://doi.org/10.1016/j.jpowsour.2013.12.101>.
- [224] Y. Yin, S.Y. Choe, Actively temperature controlled health-aware fast charging method for lithium-ion battery using nonlinear model predictive control, *Appl. Energy* 271 (2020) 115232, , <https://doi.org/10.1016/j.apenergy.2020.115232>.
- [225] X. Lin, X. Hao, Z. Liu, W. Jia, Health conscious fast charging of Li-ion batteries via a single particle model with aging mechanisms, *J. Power Sources* 400 (2018) 305–316, <https://doi.org/10.1016/j.jpowsour.2018.08.030>.
- [226] S.P. Rangarajan, Y. Barsukov, P.P. Mukherjee, In operando signature and quantification of lithium plating, *J. Mater. Chem. A* 7 (2019) 20683–20695, <https://doi.org/10.1039/c9ta07314k>.
- [227] S.P. Rangarajan, Y. Barsukov, P. Mukherjee, Anode potential controlled charging prevents lithium plating, *J. Mater. Chem. A* (2020), <https://doi.org/10.1039/d0ta04467a>.
- [228] P.M. Attia, A. Grover, N. Jin, K.A. Severson, T.M. Markov, Y.H. Liao, M.H. Chen, B. Cheong, N. Perkins, Z. Yang, P.K. Herring, M. Aykol, S.J. Harris, R.D. Braatz, S. Ermon, W.C. Chueh, Closed-loop optimization of fast-charging protocols for batteries with machine learning, *Nature* 578 (2020) 397–402, <https://doi.org/10.1038/s41586-020-1994-5>.
- [229] K.A. Severson, P.M. Attia, N. Jin, N. Perkins, B. Jiang, Z. Yang, M.H. Chen, M. Aykol, P.K. Herring, D. Fragedakis, M.Z. Bazant, S.J. Harris, W.C. Chueh, R.D. Braatz, Data-driven prediction of battery cycle life before capacity degradation, *Nat. Energy* 4 (2019) 383–391, <https://doi.org/10.1038/s41560-019-0356-8>.
- [230] E. Chemali, P.J. Kollmeyer, M. Preindl, A. Emadi, State-of-charge estimation of Li-ion batteries using deep neural networks: a machine learning approach, *J. Power Sources* 400 (2018) 242–255, <https://doi.org/10.1016/j.jpowsour.2018.06.104>.
- [231] K.T. Butler, D.W. Davies, H. Cartwright, O. Isayev, A. Walsh, Machine learning for molecular and materials science, *Nature* 559 (2018) 547–555, <https://doi.org/10.1038/s41586-018-0337-2>.
- [232] W. Li, J. Zhu, Y. Xia, W. Li, J. Zhu, Y. Xia, M.B. Gorji, T. Wierzbicki, Data-driven safety envelope of lithium-ion batteries for electric vehicles data-driven safety envelope of lithium-ion batteries for electric vehicles, *Joule* (2019) 1–13, <https://doi.org/10.1016/j.joule.2019.07.026>.
- [233] S. Yang, R. He, Z. Zhang, Y. Cao, X. Gao, X. Liu, Cyber hierarchy and interactive network (CHAIN)—enabling digital solution for battery full-lifespan management, *Matter* (2020) 1–15, <https://doi.org/10.1016/j.matt.2020.04.015>.
- [234] X. Feng, Y. Merla, C. Weng, M. Ouyang, X. He, B.Y. Liaw, S. Santhanagopalan, X. Li, P. Liu, L. Lu, X. Han, D. Ren, Y. Wang, R. Li, C. Jin, P. Huang, M. Yi, L. Wang, Y. Zhao, Y. Patel, G. Offer, A reliable approach of differentiating discrete sampled-data for battery diagnosis, *ETransportation* 3 (2020) 100051, , <https://doi.org/10.1016/j.etran.2020.100051>.