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IMPACT OF USAGE PATTERNS ON LI-ION BATTERY LONGEVITY

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Annotation. The longevity of lithium-ion (Li-ion) batteries is strongly shaped by operational usage patterns that dictate the onset and rate of degradation. Variations in depth of discharge (DoD), charge/discharge rates, and state-of-charge (SoC) management contribute significantly to performance decline, particularly under demanding operational and climatic conditions [1][4]. Frequent deep discharges accelerate electrode fatigue and electrolyte instability, while high and low C-rates amplify thermal and mechanical stress, fostering structural damage and resistive growth [2][6]. Moreover, irregular charging behavior, such as opportunistic recharging, sustains batteries at unfavorable SoC windows, enhancing side reactions such as solid electrolyte interphase (SEI) regrowth and lithium plating [4][7]. The interplay of these stressors is further intensified by extreme environmental exposure, where elevated temperatures accelerate electrolyte decomposition and low temperatures hinder ion transport, compounding degradation mechanisms [7][9]. Understanding the combined impact of usage patterns and climate factors is therefore essential for improving predictive models, guiding BMS strategies, and extending service life in electric vehicle and stationary storage applications [3][8].

Keywords: lithium-ion batteries, degradation mechanisms, charging behavior, usage patterns, depth of discharge, C-rates; state of charge, extreme climate, cycle life, capacity fade.

LI-ION BATTERIYALARINING ISHLASH MUDDATIGA FOYDALANISH TURLARINING TA'SIRI

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Annotatsiya. Litiy-ion (Li-ion) batareyalarning ishlash muddati ularning foydalanish turlari va sharoitlari bilan chambarchas bogʻliq boʻlib, bu omillar degradatsiya jarayonining boshlanishi va tezligiga sezilarli taʼsir koʻrsatadi. Zaryad chiqarish chuqurligi (DoD), zaryadlash/chiqarish tezligi va zaryad holati (SoC) boshqaruvi kabi oʻzgarishlar, ayniqsa, ogʻir ish sharoitlari va iqlimiy omillar taʼsirida batareya ishlashining pasayishiga olib keladi [1][4]. Tez-tez chuqur zaryad chiqarish elektrodlarning charchashi va elektrolitning beqarorligini tezlashtirsa, yuqori va past C-darajalar issiqlik va mexanik stressni kuchaytirib, tuzilishga zarar yetkazadi va qarshilikning oʻsishiga sabab boʻladi [2][6]. Bundan tashqari, tartibsiz zaryadlash odatlari, masalan, tasodifiy qayta zaryadlash, batareyalarni noqulay SoC oraligʻida ushlab turadi, bu esa qattiq elektrolit interfeysi (SEI) qayta oʻsishi va litiy qoplamasi kabi yon reaksiyalarni kuchaytiradi [4][7]. Ushbu stress omillarining oʻzaro taʼsiri ekstremal iqlimiy sharoitlarda yanada kuchayadi, bunda yuqori haroratlar elektrolitning parchalanishini tezlashtiradi, past haroratlar esa ion tashilishini qiyinlashtirib, degradatsiya mexanizmlarini yanada murakkablashtiradi [7][9]. Shu sababli, foydalanish turlari va iqlim omillarining birgalikdagi taʼsirini tushunish bashoratli modellarini takomillashtirish, batareya boshqaruv tizimlari (BMS) strategiyalarini yoʻnaltirish va elektromobillar hamda statsionar energiya saqlash tizimlarida xizmat muddatini uzaytirish uchun juda muhimdir [3][8].

Kalit so'zlar: litiy-ion batareyalar, degradatsiya mexanizmlari, zaryadlash odatlari, foydalanish turlari, zaryad chiqarish chuqurligi, C-darajalar, zaryad holati, ekstremal iqlim, tsikl muddati, quvvat pasayishi.

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Introduction

Lithium-ion batteries have become the backbone of modern electrification, powering electric vehicles (EVs), portable electronics, and stationary storage systems. Their high energy density and cycling capability make them indispensable; however, their longevity is significantly constrained by operational and environmental stresses [4][8]. Unlike controlled laboratory testing conditions, real-world usage patterns are irregular, shaped by user behavior, charging convenience, and environmental variability [1][3]. Such non-uniform cycling and charging practices often expose batteries to high depths of discharge, rapid charge/discharge rates, or prolonged operation at extreme states of charge, thereby accelerating degradation processes such as capacity fade, impedance growth, and loss of lithium inventory [2][4][7].

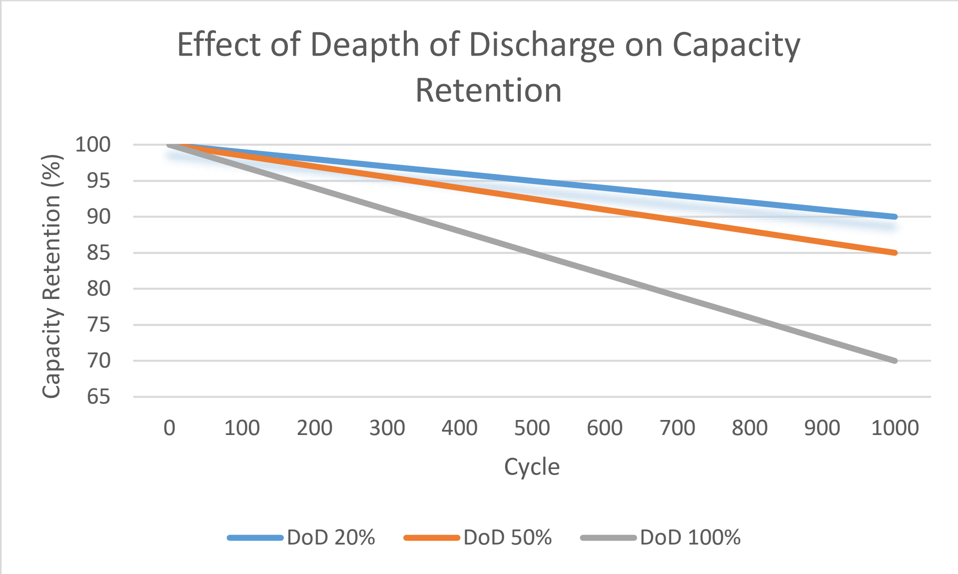
Recent studies emphasize that operational usage patterns exert degradation effects comparable to, or greater than, intrinsic material limitations [7][9]. For instance, sustained high SoC accelerates SEI thickening and transition metal dissolution, while repeated deep discharges lead to structural fatigue of electrodes and irreversible capacity loss [1][4]. Similarly, aggressive C-rate operations impose severe thermal loads, heightening mechanical stress and fostering side reactions [2][6]. These impacts are magnified under extreme climates, where high ambient temperatures accelerate electrolyte breakdown, and cold conditions impair ionic conductivity and promote lithium plating during charging [7][9].

Therefore, a comprehensive understanding of the influence of usage patterns is vital not only for accurate service life prediction but also for guiding the design of advanced battery management strategies. By integrating insights on DoD, C-rate, SoC management, and charging behaviors with environmental effects, robust frameworks can be established for mitigating degradation and extending battery longevity in both automotive and stationary applications [3][5][8].

Impact of Usage Patterns

Fast Charging

Frequent deep discharges (high Depth of Discharge cycles), accelerating capacity loss [1][4][7]. *Depth of discharge* (DOD) - indicates the percentage of the battery that has been discharged relative to the overall capacity of the battery [2][6]. Depth of Discharge is defined as the capacity that is discharged from a fully charged battery, divided by battery nominal capacity. DoD is a critical factor affecting the cycle life of lithium-ion batteries [3][7]. Frequent deep discharges where a battery is regularly drained close to 100% impose significant mechanical and chemical stress on the electrodes, leading to capacity fade and premature aging. These full-range cycles cause excessive expansion and contraction of electrode materials, promote the breakdown and regrowth of the SEI, and increase lithium plating and electrolyte decomposition [1][4][7]. Collectively, these mechanisms accelerate irreversible degradation.



The graph above illustrates the relationship between DoD levels and capacity retention over 1,000 cycles.

Batteries cycled at shallow depths (20% DoD) retain around 90% of their original capacity after 1,000 cycles. In contrast, batteries subjected to full-depth cycles (100% DoD) lose nearly 30% of their capacity in the same period [3][8]. This empirical trend underscores the detrimental impact of high DoD cycling on long-term battery health. Despite this, many EVs are operated without optimization of the DoD window, exposing their battery packs to deep cycling that compromises safety and performance. This gap highlights the need for data-driven strategies to evaluate and mitigate degradation arising from deep discharge behaviors [5]. Maintaining optimal SoC is essential for maximizing the performance and lifespan of lithium-ion batteries. Frequent discharging below 20% SoC especially in EV applications can lead to several adverse electrochemical and operational effects that accelerate battery degradation. At low SoC levels, the potential of the anode drops significantly, increasing the risk of lithium plating during subsequent charging. This results in the formation of metallic lithium on the anode surface, which reduces the amount of cyclable lithium, diminishes capacity over time, and can potentially lead to dendrite formation and internal short circuits.

Moreover, operating at low SoC may destabilize the SEI layer, a critical barrier that protects the anode [4][7]. As the SEI breaks down and reforms, more lithium is consumed in the process, compounding irreversible capacity loss [1][8]. When the cell voltage falls near its lower limit typically around 2.5–3.0V per cell it also increases the risk of copper dissolution from the anode current collector. Dissolved copper can redeposit elsewhere in the cell, creating conductive pathways that may lead to micro-short circuits and, in severe cases, thermal runaway [3][9]. Additionally, batteries discharged below 20% exhibit higher internal resistance, leading to greater heat generation and lower energy efficiency during the next charging phase. In cold environments, this condition is further exacerbated due to reduced ion mobility, increasing the chances of lithium plating and SEI degradation. Low SoC operation also challenges the precision of BMS. These systems rely on voltage and current data to estimate SoC. When operating near the voltage floor, the voltage-to-SoC relationship becomes nonlinear and unpredictable, reducing estimation accuracy and potentially compromising system safety and control. Given these risks, modern BMS architectures often enforce SoC buffers, avoiding regular operation below 20% except when absolutely necessary [3][5]. From a lifecycle management perspective, enforcing controlled SoC limits is an effective strategy to preserve battery health, extend usable life, and minimize safety hazards.

High C-Rates

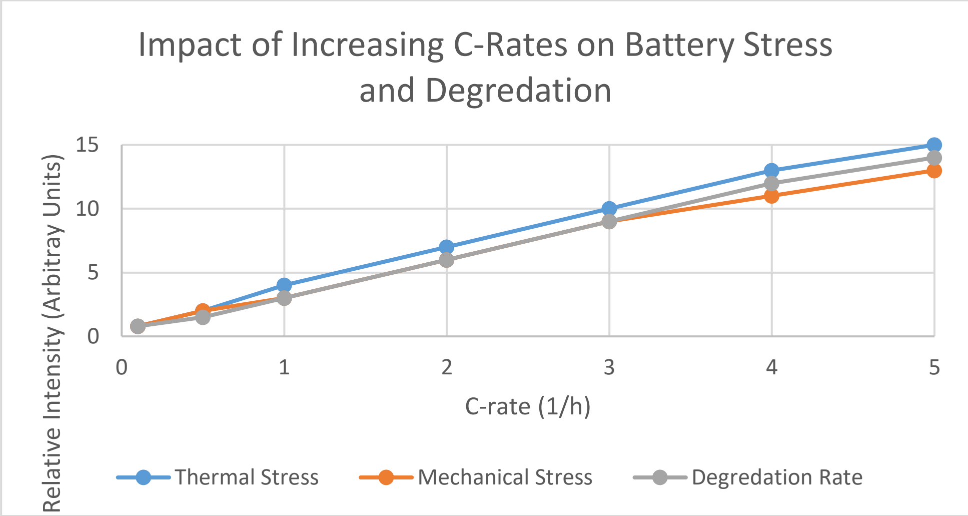
High and low charge/discharge rates (C-rates), causing mechanical stress and excessive heat generation - The performance, safety, and lifespan of lithium-ion batteries are significantly influenced by their charging and discharging rates, commonly expressed in terms of C-rates [2][6]. Understanding the effects of both high and low C-rates is essential, especially in applications such as EVs, where dynamic power demands are common. This chapter explores how varying C-rates contribute to mechanical stress, thermal behavior, and electrochemical degradation within Li-ion batteries, laying a foundation for proposing optimized operational strategies.

The C-rate is a standardized metric that quantifies the rate at which a battery is charged or discharged relative to its nominal capacity. A 1C rate indicates a complete charge or discharge within one hour, whereas a 0.5C rate implies a two-hour duration. High C-rates (e.g., >1C) are desirable for fast charging and high-power discharges, while low C-rates (e.g., <0.5C) are often preferred for extending battery life and ensuring safety. However, each has distinct implications for battery degradation mechanisms, particularly regarding thermal and mechanical stress.

High C-rates - subject lithium-ion batteries to elevated electrical, thermal, and mechanical stress levels [1][7]. The rapid movement of lithium ions between the electrodes can lead to several adverse phenomena:

At higher C-rates, internal resistance within the battery causes significant heat accumulation due to Joule heating (I^2R losses). This thermal buildup, if not adequately managed, may result in increased risk of thermal runaway a critical safety hazard in high-energy battery systems. Furthermore, elevated temperatures accelerate the decomposition of the electrolyte and other components, leading to the formation of SEI layers and gas generation [4][7].

The rapid intercalation and deintercalation of lithium ions induce expansion and contraction in electrode materials. These volumetric changes generate mechanical stress, leading to: a) Micro-cracking of active electrode materials, b) delamination of electrode coatings, c) structural fatigue and particle disintegration [1][4][7]. Such mechanical degradation not only reduces capacity retention but also impairs ionic conductivity and increases internal resistance over time. Under high charging rates, especially at low temperatures or high SoC, lithium plating may occur on the anode surface [7][9]. This phenomenon involves the deposition of metallic lithium rather than its intercalation into the graphite structure, posing significant safety concerns due to potential dendrite formation and internal short circuits. The combined effects of heat generation, mechanical damage, and side reactions at high C-rates contribute to rapid degradation of battery performance . High C-rate cycling has been correlated with faster capacity fade and reduced calendar life, limiting the long-term usability of the battery [2][6][8].



Here's a concise explanation of how thermal stress, mechanical stress, and degradation rate increase with higher C-rates.

While *low C-rates* - are generally beneficial for extending battery life, they also come with trade-offs in terms of performance:

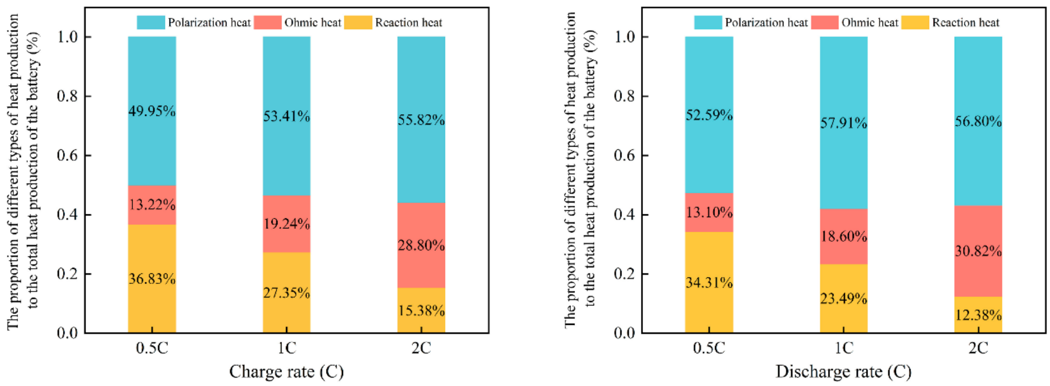
Lower current flow at reduced C-rates generates less heat within the cell, mitigating thermal stress and reducing the likelihood of thermal decomposition or runaway. This enables safer operation and reduces the need for aggressive thermal management strategies.

The slower diffusion of lithium ions into electrode materials minimizes mechanical strain, leading to: a) Lower crack propagation, b) Stable SEI formation, c) enhanced structural integrity of electrodes.

These benefits contribute to improved cycle life and more consistent performance over time.

Slow charging significantly reduces the chance of lithium plating, even at lower temperatures, thereby enhancing the overall safety and reliability of the battery system.

Despite these advantages, low C-rates may not be suitable for all applications, particularly those requiring high power output or rapid charging capabilities.

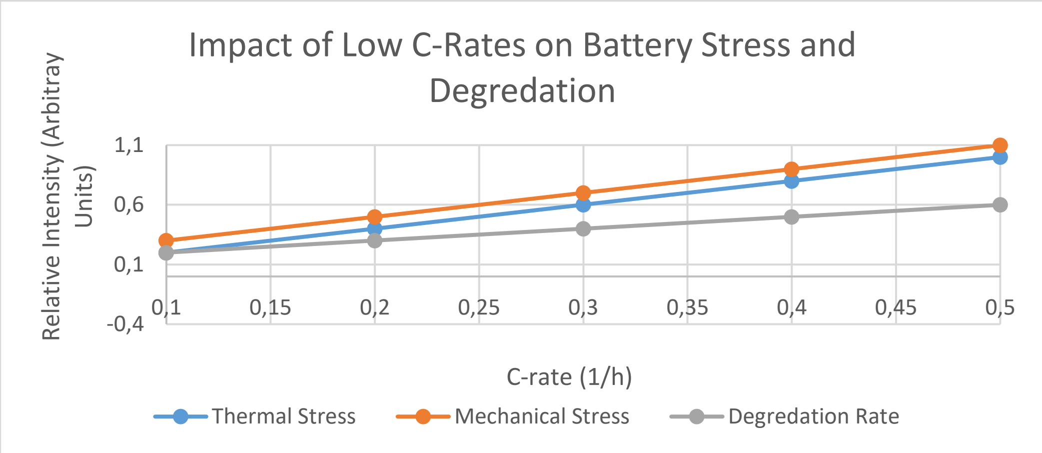


(a) (b)

Figure a,b shows the proportion of reaction heat, polarization heat, and ohmic heat to the total heat production of the battery at different rates of charge and discharge, respectively.

The drawing results reveal that the polarization heat at the charging rates of 1 C and 2 C. Moreover, three discharge rates occupy half or more of the total heat production. The ohmic heat is relatively stable. With the increase in the discharge rate, the ohmic heat increases slightly. At the same time, the reaction heat corresponds to the continuous decrease. When the discharge rate is 2 C, the proportion is as low as 12.38%, and the heat production decreases obviously.

In EVs, for example, low C-rates may limit acceleration or prolong charging times, reducing vehicle usability. While safer, low C-rate charging is time-intensive and unsuitable for high-demand applications. In commercial EV use, this limitation can lead to extended downtime and poor customer satisfaction, making smart scheduling and adaptive charging essential.

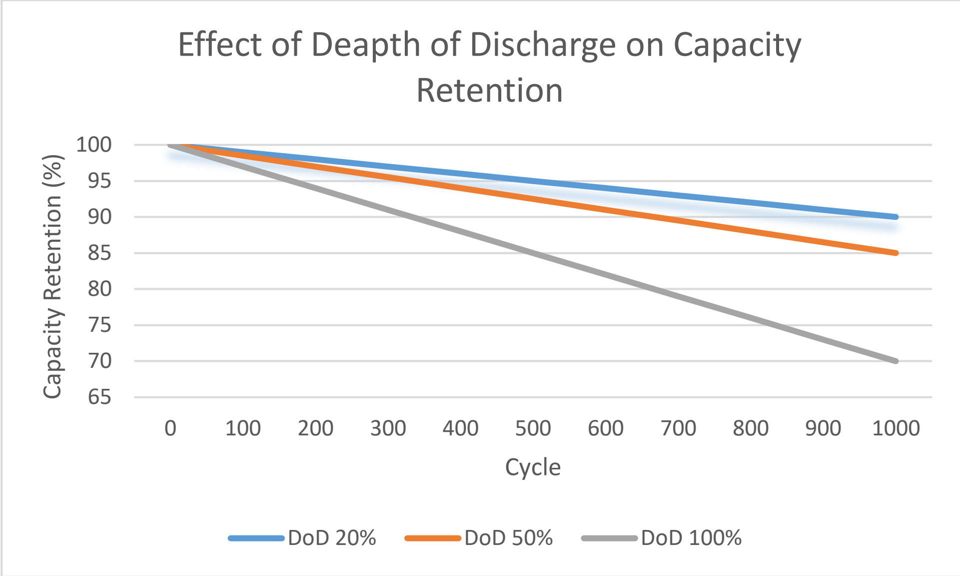


Here is the graph showing how thermal stress, mechanical stress, and degradation rate remain low and stable at low C-rates.

As EVs become more widespread, effective charging strategies are essential to balance user convenience, grid stability, and long-term battery health. Traditional charging methods often rely on fixed schedules or static rules that fail to reflect the complex and dynamic conditions of real-world EV usage. These rigid strategies can expose lithium-ion batteries to harmful thermal and mechanical stresses, especially under high C-rate operations, leading to premature capacity loss and increased safety risks. Smart charging protocols - dynamically adjust current flow based on a battery's real-time health status, usage pattern, ambient conditions, and user needs. These strategies aim to optimize charging speed without incurring excessive thermal or mechanical stress.

Depth of Discharge (DoD) and Cycling Profiles

Frequent deep discharges (high Depth of Discharge cycles), accelerating capacity loss [1][4][7]. *Depth of discharge* (DOD) - indicates the percentage of the battery that has been discharged relative to the overall capacity of the battery. Depth of Discharge is defined as the capacity that is discharged from a fully charged battery, divided by battery nominal capacity [3][7]. DoD is a critical factor affecting the cycle life of lithium-ion batteries. Frequent deep discharges where a battery is regularly drained close to 100% impose significant mechanical and chemical stress on the electrodes, leading to capacity fade and premature aging. These full-range cycles cause excessive expansion and contraction of electrode materials, promote the breakdown and regrowth of the SEI, and increase lithium plating and electrolyte decomposition. Collectively, these mechanisms accelerate irreversible degradation [6][9].



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Moreover, operating at low SoC may destabilize the SEI layer, a critical barrier that protects the anode. As the SEI breaks down and reforms, more lithium is consumed in the process, compounding irreversible capacity loss. When the cell voltage falls near its lower limit typically around 2.5–3.0V per cell it also increases the risk of copper dissolution from the anode current collector. Dissolved copper can redeposit elsewhere in the cell, creating conductive pathways that may lead to micro-short circuits and, in severe cases, thermal runaway [3][9].

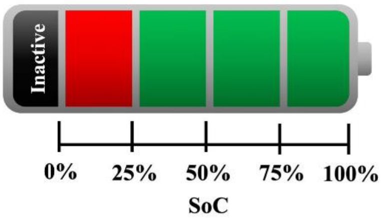
Additionally, batteries discharged below 20% exhibit higher internal resistance, leading to greater heat generation and lower energy efficiency during the next charging phase. In cold environments, this condition is further exacerbated due to reduced ion mobility, increasing the chances of lithium plating and SEI degradation [7][9]. Low SoC operation also challenges the precision of BMS. These systems rely on voltage and current data to estimate SoC. When operating near the voltage floor, the voltage-to-SoC relationship becomes nonlinear and unpredictable, reducing estimation accuracy and potentially compromising system safety and control.

Given these risks, modern BMS architectures often enforce SoC buffers, avoiding regular operation below 20% except when absolutely necessary. From a lifecycle management perspective, enforcing controlled SoC limits is an effective strategy to preserve battery health, extend usable life, and minimize safety hazards.

State of Charge (SoC) Management

Inconsistent SoC management, resulting in capacity imbalances and early degradation [4][7]. SoC is the measure of the remaining energy in a battery. Physically, the amount of energy left in a battery (ψ) is defined as the average concentration of lithium-ions in the cathode ($C_{s,vg}$) over the maximum possible concentration [2][6]:

$$\psi = \frac{C_{s,avg}}{Cs}$$

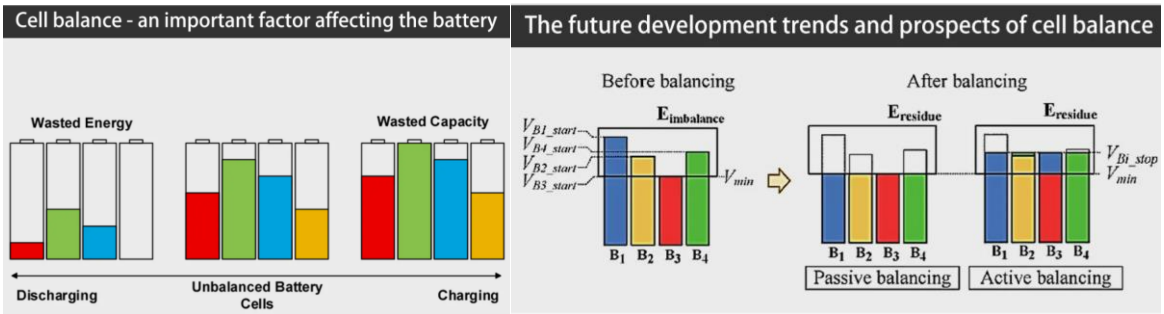


Stored energy status of a lithium-ion battery related to state-of-charge.

SoC imbalance often arises from *cell imbalance*. This refers to *differences in voltage, capacity, or internal resistance* between individual cells in a battery pack [3][6]. Even if the cells are charged or discharged together, slight variations over time (due to aging, temperature, manufacturing inconsistencies) can cause them to behave differently (One cell reaches 4.2V while others are still at 4.0V during charging) [5][8]. Battery imbalance can have a serious impact on battery performance and usage efficiency. First, cell imbalance will cause the overall performance of the battery pack to degrade. Some cells may be overcharged or overdischarged during the battery charging and discharging process of the battery pack, thus affecting the performance of the entire battery pack. Secondly, battery imbalance will also increase energy loss. Due to the imbalance of each cell, the battery pack will generate additional energy loss during the charging and discharging process, reducing the battery's efficiency. In addition, unbalanced batteries may also cause safety hazards. Due to the imbalance of each cell, some cells may overheat during the charging and discharging process of the battery pack, causing safety hazards.

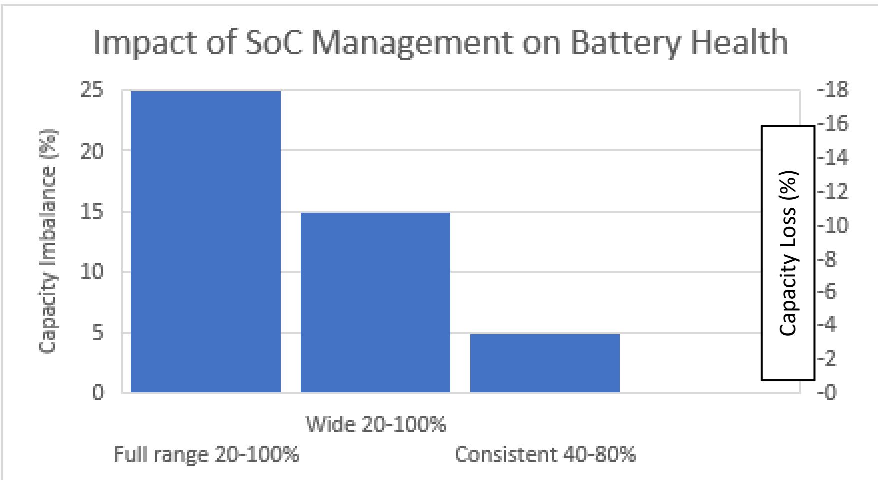
To address battery imbalance, it is essential to develop efficient and stable cell balancing algorithms supported by appropriate optimization strategies. Designing such algorithms requires a comprehensive understanding of key factors, including battery cell characteristics, suitable balancing approaches, and implementation technologies [3][6].

First, a thorough analysis of individual cell properties such as capacity, internal resistance, and voltage is necessary [2][6]. Based on these characteristics, an appropriate balancing strategy must be selected, whether voltage-based, current-based, or energy-based. Finally, the chosen algorithm should be implemented using suitable technical means, such as digital signal processors (DSPs) or programmable logic controllers (PLCs), to ensure precise and reliable control [5][8].



SoC imbalance refers to differences in the charge levels of individual cells within a battery pack [1][7]. While an ideal pack would have all cells charged and discharged uniformly, various factors such as manufacturing inconsistencies, uneven aging, temperature gradients, and self-discharge rates can lead to disparities in SoC. This imbalance results in certain cells reaching their charge or discharge limits earlier than others, reducing the overall usable capacity of the battery pack [3][7]. Moreover, persistent SoC imbalance can increase the risk of overcharging or over-discharging specific cells, potentially accelerating degradation and compromising safety [1][7][9]. To address this issue, Battery Management Systems (BMS) employ cell balancing strategies to align the SoC levels of all cells, thereby enhancing performance, extending battery life, and ensuring safe operation.

Lithium-ion batteries function optimally when operated within a moderate and consistent SoC range. However, real-world usage often subjects batteries to wide SoC fluctuations, from shallow cycling to full 0–100% usage, which can lead to early degradation. The graph below illustrates how such inconsistent SoC management results in significant capacity imbalance (up to 25%) and accelerated capacity loss (up to 18%) [5][8].



Here is a visual representation of the Impact of State of Charge (SoC) Management on Battery Health, showing how different SoC ranges affect capacity imbalance and degradation. (Blue Bars: Show Capacity Imbalance (%) increases with wider SoC usage.)

This degradation is primarily due to localized over-lithiation and under-lithiation at electrode surfaces, especially near voltage extremes, which promotes SEI growth, transition metal dissolution, and lithium plating [1][7][9]. Over time, this leads to uneven aging across cells in a battery pack, reducing overall energy efficiency and increasing thermal and safety risks [4][9].

Conclusion

The analysis of lithium-ion battery longevity under irregular usage patterns and extreme climate conditions highlights the multidimensional nature of degradation [1][3][5]. Frequent deep discharges accelerate electrode fatigue and electrolyte instability, while high C-rates impose thermal and mechanical stresses that amplify side reactions and structural damage[2][4][7]. Conversely, inconsistent SoC management and opportunistic charging sustain cells at harmful operating windows, intensifying solid electrolyte interphase (SEI) growth, lithium plating, and cell imbalance. Importantly, these stressors seldom act independently; their interplay with environmental extremes, such as low-temperature ion transport limitations or elevated-temperature electrolyte decomposition, results in synergistic degradation mechanisms that shorten service life far beyond predictions from isolated laboratory tests [3][7][8].

Mitigation of these challenges requires the integration of optimized charging strategies, SoC-aware usage protocols, and intelligent battery management systems (BMS) [4][6]. Enforcing SoC buffers, limiting high-depth discharges, moderating C-rates, and employing dynamic balancing algorithms can significantly slow degradation and improve long-term safety [2][5][8]. Moreover, smart charging protocols, leveraging real-time diagnostics and predictive modeling, hold promise for harmonizing user convenience with system reliability [1][7][9].

Future research must therefore focus on adaptive control strategies that link user behavior, environmental variability, and electrochemical state estimation in real time. By adopting such holistic approaches, it becomes possible to extend battery cycle life, lower lifecycle costs, and accelerate the sustainable deployment of electric vehicles and energy storage systems [2][4][8].

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