

Review

Article

Degradation mechanisms and performance merits of vehicular Lithium batteries: A comparative review

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Abstract

Battery degradation, degradation mechanisms electric vehicles, lithium-ion.

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Norhan H. Elgouhary, Department of Electromechanical Engineering, Benha University, Benha, Egypt, **Tel.:** 01023698778, **Email:** nourhan.hany@bhit.bu.edu.eg The world faces an increasing threat of environmental pollution and fossil fuel depletion. Therefore, many legislative and technical efforts have been done to promote the use of renewable energy sources for the transportation sector. The most crucial part of the elec- tric vehicle is the energy storage system, and among the various storage technologies, batteries are the most prominent in electric vehicles. Thus, the energy storage system is the core of electric propulsion system implementation in vehicles. Battery packs using lithium-ion cells are widely used for electrified drive-lines, owing to their specific energy and power. Also, they are lighter and last longer than other types of cells. This paper provides a comprehensive review of electric vehicle battery development, focusing primarily on lithium-based batteries. This review covers the material structure, advantages, disadvantages, and thermal characteristics of different types of Li-ion batteries. Also, battery degradation is a major challenge for electric vehicle applications. Degradation shortens the battery's lifetime, reduces its maximum capacity, and affects driving range and performance. In this regard, the paper furthermore reviews the degradation of Li-ion batteries by discussing the degradation mechanisms on the cathode, anode, and electrolyte. As well as, the key factors that affect degradation. The presented review provides a comprehensive picture of current Li-ion battery technology, a description of battery degradation, and solutions to decelerate its degradation. It also explores areas that academic researchers and industrial partners can further explore to achieve electric vehicle performance goals and provides important guidance..

1. INTRODUCTION

The advent of Electric Vehicles (EVs) marks a significant turning point in transportation, offering an ideal solution to mitigate the environmental impacts associated with traditional Internal Combustion Engine Vehicles (ICEVs). By leveraging electric power as an alternative to fossil fuels, EVs present a multitude of environmental benefits that extend far beyond merely reducing tailpipe emissions. The most significant advantage of electric and hybrid vehicles is that they play a pivotal role in reducing greenhouse gas emissions and reducing reliance on limited fossil fuel resources, thus promoting a cleaner and more sustainable transportation ecosystem. Statistical records show that the transportation industry, particularly road transportation, is responsible for around 28% of the total carbon dioxide (CO_2) emissions. Therefore,

many governments worldwide are implementing diverse initiatives, regulations, and programs to encourage shifting to electrified vehicles^[1].

EV batteries are considered the most critical component as well as the main obstacle to wider adoption of EVs. Since the beginning of the EV technology, different types of battery technologies have been used, ranging from leadacid to lithium-ion batteries. Later, lead-acid prototype has been implemented into the first EV. In 1899, the nickelcadmium battery was introduced, which showed significant improvements in its capacity. However, it also suffered from aging issues and memory effects^[2].

In 1991, commercial production of lithium-ion batteries began. Their use in EVs marks a significant transition for the EV industry. Lithium-ion batteries are a highly promising battery technology as they provide a compact and lightweight solution for high-energy storage, with an energy density of 240-280 Wh/L and a specific energy of 120-140 Wh/kg. Therefore, lithium-ion batteries are uniquely qualified with superior performance features, making them a suitable replacements for heavier and less efficient batteries such as nickel-cadmium and lead-acid batteries. At present, lithium batteries dominate the EV market^[3].

Full-scale EV adoption faces many challenges, especially in the Energy Storage System (ESS); the most crucial one is specific power/energy. As power must be constantly provided to continue their movement, which makes increasing the power capacity essential. Battery degradation also poses a major challenge to the adoption of EV technology in terms of durability and reliability. Battery degrades and loses capacity over time and use, resulting in a reduction in its capacity to store and deliver energy. Degradation is also affected by driving behavior, storage conditions and charge and discharge cycles^[4].

The most significant operational factors that primarily affect battery degradation are temperatures, variations in the State of Charge (SoC), and charge and discharge current rates. The C-rate in electric batteries stands for the charge or discharge rate relative to the battery's capacity. It is well known that high temperatures can adversely affect battery aging. However, low temperatures also cause serious issues for the battery. Storing or cycling at a higher SoC accelerates battery degradation compared to a lower SoC. However, if the SoC is extremely low, it would significantly impact the battery's lifespan. High C-rates also further reduce battery capacity, especially at high temperatures^[5].

Many different studies have been conducted on Li-ion battery degradation. It has been proven that the degradation of Li-ion batteries occurs as a result of a variety of chemical and physical processes that affect different parts of the battery. The most common degradation mechanism is the formation of the Solid Electrolyte Interphase (SEI). The formation of SEI hinders the interaction between lithium ions and the electrodes, contributing to the degradation of the cell as the film grows thicker. Furthermore, the battery could lose 10% of its initial capacity due to the formation of SEI film^[6].

Comprehending the mechanisms underlying the degradation of Li-ion batteries can aid in reduce degradation, as contributes to an improvement in ESS design^[7]. Therefore, significant progress has been achieved in the advancement of battery technology to meet higher performance goals, especially regarding driving range and lifespan. In fact, during the last decade, the specific energy of a lithium-ion battery cell has nearly doubled, reaching a value of 240 Wh/kg. Nevertheless, it needs to be higher than 1700 Wh/kg to compete with internal combustion engine vehicles (ICEVs)^[8].

In light of the above discussed challenges of batteries as energy storage sources in EVs, the following conclusions can be put forward: firstly, Lithium-ion batteries offer several advantages over other rivals' batteries, including higher energy density, longer lifespan, and faster charging capabilities. These attributes make them ideal for powering EVs, enabling greater driving range and improved performance. Secondly, the degradation rate in Li-ion batteries is a complex phenomenon that attracts the attention of many researchers to investigate its influencing and dominant variables. It can manifest through various processes, including capacity fade, electrode material degradation, and electrolyte decomposition. Therefore, it needs to be well understood to ensure long-term performance and reliability. Finally, factors such as operating temperature, charging and discharging rates, and depth of discharge significantly influence battery degradation rates.

To address the challenges described above, this paper is organized as follows. Section 2 deals with the evolution of electric batteries, explaining their specifications, especially lithium batteries, how they work, the most often used materials, and their chemical structure features. Li-ion battery degradation mechanism and its negative impact are discussed in section 3. In section 4, the effect of various variables on battery degradation is reviewed. Section 5 summarizes the methods and practices for extending battery life. Finally, the main insights and key findings of this study are given in section 6.

2. FROM LEAD-ACID TO LITHIUM-ION: EVOLUTION OF BATTERY CHEMISTRIES IN ELECTRIC VEHICLES

The electric battery is an electrochemical device consisting of several cells. Each cell consists of a cathode and anode, with an electrolyte solution acting as a medium for ion exchange between the two electrodes. The cells are interconnected either in series or in parallel to provide the desired voltage and capacity, respectively. The battery generates electricity and stores energy by applying a voltage to the battery terminals and causing chemical reactions internally. For discharging, the internal reaction is reversed^[4].

Many types of batteries have been used as propulsion energy sources for the electrification of vehicles. Leadacid batteries have been typically used for many decades in conventional vehicle; however, they are hardly suitable to empower electric drive-lines due to their unfavorable characteristics, i.a. low specific power/energy and the difficulty to recycle its knocked raw material^[1].

Lead-acid batteries were soon substituted by nickelbased batteries, specifically nickel- cadmium (Ni–Cd) and nickel-metal hydride (Ni-MH) batteries. The nickel-based battery is an advanced technology and has double the energy density compared to the lead-acid battery. Although Ni–Cd batteries have the highest life cycle and can be fully discharged without damage, they are inadequate for electrified vehicle applications due to their high memory effect and cadmium metal toxicity. Because of these drawbacks, Ni-MH batteries are presently replacing Ni–Cd. Ni-MH batteries use Metal Hydride for negative electrodes



instead of cadmium (Cd). Despite their widespread use in hybrid vehicles over the past decade, these batteries also exhibited several drawbacks. These include a high selfdischarge coefficient, low charge and discharge efficiency, poor performance at low temperatures, and a memory effect^[1].

Zebra batteries are nickel-based ones which also contain sodium and chloride. Which offer many features, such as high specific energy and lower costs than others. However, their disadvantages are its low specific power and safety, in addition to storage problems. These batteries require temperature control due to their high operating temperature (300°C). Due to Zebra's low specific energy, it cannot be the energy source for EVs; therefore, it is combined with another energy source, such as supercapacitors^[1].

Additionally, there is the sodium-sulfur (Na-S) battery, which is considered one of the most advanced battery technologies. This battery has high energy density and high efficiency which extended its life. In addition, it is capable of reaching operating temperatures ranging from 300°C to 350°C. The Ford Ecostar, introduced in 1992-1993, uses this type of battery^[9].

The evaluation of different battery types is based on their energy density, power density, and cycle life. Among all types of batteries, Lithium-Ion Batteries (LIBs) dominate the auto- motive market due to their significant features in terms of these crucial characteristics and play a pivotal role in the widespread adoption of electric vehicles. The dominance of LIBs is due to their high energy density, power density, precise memory effect, long cycle life, low self-discharge rate, and high-efficiency rate (more than 99%). But, they are more costly com- pared to lead-acid and Ni-MH batteries^[10,11]. Figure 1 compares LIBs to other battery technologies in terms of energy density and specific energy.

The essential operation of LIBs is the movement of lithium ions and electrons between the electrodes during charge and discharge cycles. In discharge mode, the lithium intercalated between the layers of carbon graphite begins to liberate electrons, which flow to the cathode through an external circuit. Simultaneously, the positive Li-ions are also liberated from the anode and migrate to intercalate into the cathode, but through the electrolyte. The electrolyte is ionically conductive, allowing Li-ions to travel between the anode and cathode, but is an insulator to electrons. A separator separates the cathode and anode from each other, thus avoiding a short circuit while enabling the flow of Li-ions. When charging, the travel of Li-ions and electrons is reversed by the external voltage, and the energy is stored^[12].



Fig. 1: Ragone plot of various battery types (based on^[4]).

The lithium battery's characteristics are defined by the careful selection of materials for the electrodes. As well as, the cost, performance, and capacity of the battery. Figure 2 illustrates the various materials commonly used in Li-ion batteries. This variety of construction materials allows for a wide variety of LIB types.

2.1. Lithium Cobalt Oxide (LCO)

LCO batteries are widely utilized in electrified automobiles; due to their low specific power and high

specific energy, they could be combined with another battery with a high specific power in a single power supply. They also achieved reasonably reliable efficiency^[13].

The theoretical capacity of LCO is about 274 mAh/g excluding lithium from the electrode, although, for a long time, the capacity fell to about 135 mAh/g. The operating voltage of LCO increased from 4.25 V to 4.45 V, increasing capacity to 175 mAh/g and energy density from 200 Wh/L to 700 Wh/L^[14]. But, these batteries have some drawbacks such as expensive prices due to limited cobalt reserves, the

need for protection during fast charging, a limited lifespan, and thermal instability. Therefore, adding aluminum and nickel leads to more stability in the cell and a safer battery^[15].

2.2. Lithium Nickel Manganese Cobalt Oxide (NMC)

NMC batteries use a combination of nickel, manganese, and cobalt as cathode materials. This combination is complementary because nickel has high specific energy, while manganese can achieve low internal resistance. The balance between elements can be adjusted to create a high energy density or power density, such as NMC 111 (equal proportions nickel, manganese, and cobalt), NMC 532, and NMC 622. Increased nickel in the cathode enhances energy density and reduces cost due to reduced cobalt^[3]. NMC batteries exhibit good thermal stability and are less prone to voltage fade compared to some other Li-ion batteries. The operating temperatures for discharge mode are 20°C to +55°C, and 0°C to +55°C in charging mode^[16].



Fig. 2: Various materials for in Li-ion battery segments(based on^[12]).

Although NMC batteries use less cobalt compared to some other batteries like LCO, they are still relatively expensive, which can impact battery costs and supply chain sustainability.

2.3. Lithium Manganese Oxide (LMO)

LMO batteries are also known as spinel batteries. The cubic spinel structure of these batteries has several advantages, the most important of which is reducing the internal resistance of their cell. This allows fast charging and a high discharge current of 30A. LMO has better thermal stability than LCO and offers a good balance between power and energy density. It renders them appropriate for automobiles with high electrical output and adequate storage for electricity. Although it has a lower specific energy than LCO, it provides 50% more energy than nickel-based batteries^[17].

However, its capacity is 33% less, and there is more capacity loss during charging and discharging cycles because of manganese cite fragmentation. They also suffer from a limited lifespan. LMO batteries may experience voltage fade over time, where the voltage drops more rapidly than in other lithium-ion chemistries. This can have an impact on the apparent SoC as well as the total battery efficiency^[18].

Despite LMO's limitations, it has a significant cost advantage over other lithium batteries, making it vital to promoting the commercial use of EVs. Therefore, most LMO batteries are combined with NMC to enhance the specific energy and extend the lifespan. The combination of LMO and NMC technologies enhances the performance of each component. When LMO provides a large current increase during acceleration, NMC provides a long driving range. This LMO/NMC combination is frequently found in the BMW i3, Chevy Volt, and Nissan Leaf^[19].

2.4. Lithium Iron Phosphate (LFP)

LFP batteries operate more reliably at elevated temperatures compared to other lithium-ion chemistries as the phosphate offers better stability for the cathode in cases of overcharging, superiority in high temperatures, and security than lithium manganese oxide and lithium cobalt oxide. LFP batteries have an operating temperature range from -30°C to +60°C for a unit cell and from



 50° C to $+60^{\circ}$ C for a pack. They are also less susceptible to thermal run away. LFP battery demonstrates many features such as high current handling capacity, long cycle life, high specific power for almost 160 mAh/g, low resistance, and low cost^[20].

LFP batteries have a higher self-discharge rate, which can cause balancing concerns with aging, reducing their capacity to deliver constant and stable electric power. In addition, this battery has drawbacks with aging due to temperatures. But due to its ability to handle allowable current, the battery does not need a heating or liquid cooling system^[16]. Thus far, LFP technology has been extensively employed in many electric vehicles, including the BYD (e6), BMW Active Hybrid 3, and Chevrolet Spark^[21].

2.5. Lithium Nickel Cobalt Aluminum Oxide (NCA)

NCA batteries have the same specific power, specific energy, and lifetime as nickel manganese batteries. However, they are more expensive and require safety monitoring as they are considered less safe than other types of Li-ion batteries. It is interesting to note that these two batteries lose 60% and 40% of their energy density, respectively, when they operate at 18°C. Therefore, NMC and NCA batteries require a heating system to maintain the temperatures between 0°C to 40°C^[22].

Although NCA is more expensive than spinel LMO, it has a variety of benefits, including a extended lifespan, a greater specific capacity, and a high specific energy. It is expected that by 2025, the energy density of NCA will reach 700 Wh/L at the level of individual cells. Thus far, NCA technology has effectively been utilized in electric vehicles, specifically Tesla Model X, Model S, and Model 3^[23].

2.6. Lithium Titanate (LTO)

Contrary to all listed lithium batteries, the anode of this battery is lithium titanate, not graphite, with a spiral structure. This is because graphite suffers from the formation of lithium dendrites when overcharged. These issues can result in internal short circuits and cause safety issues such as the risk of fire or explosion. LTO provides the highest performance among the commercially available lithium batteries. Additionally, lithium titanate provides a large capacity, a high rate of charge and discharge, and a long lifetime due to unchanged electrodes' volume during lithiation. Furthermore, LTO is capable of functioning in both high-temperature and low-temperature environments, ranging from -30°C to 60°C. It is noteworthy that

even at -30 °C, it can still achieve 80% of its maximum capacity^[24].

These advantages have the potential to significantly enhance traditional LIBs for use in electrified vehicles in the near future. Nevertheless, there are still many challenges that need to be over-comed for LTO anodes to achieve success in EV applications. These challenges include limited energy density and high-power capabilities to meet the fast charging and discharging requirements of vehicle batteries^[25].

Each type of these batteries has unique specifications, which are crucial in deciding which battery fulfills the best performance especially, since they used to empower the engines. Consequently, many battery technologies have been developed, and extensive research has been conducted to achieve equivalent performance between electric propulsion systems and internal combustion engines in terms of power, range, cost, and reliability. For this reason, making the right battery choice requires understanding the benefits and drawbacks of each type. Some systems require high power, others need lightweight and small volume, but long life is the most commonly desired feature. Table 1 compares the characteristics, advantages, and drawbacks of various battery technologies.

3. DEGRADATION OF LI-ION BATTERIES

Degradation is a key disadvantage of Li-ion batteries. It minimizes the battery's life, diminishes its ability and performance, and imposes significant expenses on individuals. Degradation is caused by a multitude of physical and chemical processes that affect almost every component of the battery, including electrodes, electrolytes, separators, and current collectors^[26].

Degradation of batteries can be identified through two conceptual phenomenon, namely power- and capacity-fade. Power fade of the battery indicates the augmented lack of ability to deliver the initial throughput over time. On the other hand, capacity fade refers to the degraded ability store the same energy after several cycles of charging and discharging^[26,27].

It is commonly recognized, that losing 20% of the initial capacity of the battery indicates reaching its end of life (EoL) [28]. During initial cycles, batteries lose 10% of their capacity because of the creation of a Solid Electrolyte Interface (SEI). Furthermore, excessive temperatures, a high cycle rate, a high Depth of Discharge (DoD), and a significant SoC speed up capacity fade^[29].

Battery type	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Specific Power (W/kg)	Cycle Life	Operating Temperature (°C)	Nominal Voltage (V)	Efficiency (%)	Advantages	Disadvantages
L e a d acid	30-50	60-100	200-400	2000- 4500	-20 to +60	2	70-90	-High specific power. -High efficiency. -Low cost.	-Low specific energy. -Limited service life.
Ni-MH	50-70	100-140	150-300	500- 3000	-40 to +50	1.25	50-80	-High specific energy. -Large temperature range. -Safety. -Long service life.	-High self discharge -High cost -Memory effect
Ni-Cd	40-50	80-100	150-350	2000- 3000	-40 to +60	1.25	60-90	-High specific energy. -No degradation for deep charge or discharge. -Long lifetime.	-Cadmium toxicity -High cost -Recycling issues
Li-ion	120-140	240-280	200-300	1500- 4500	-20 to +60	3	70-85	 High energy density. High specific energy. High specific power. High voltage operation. No memory effect Lighter and smaller Low self-discharge Long cycle life 	-High cost Affected by temperature - R e q u i r e d overcharge and over-discharge protection -Fragile
Li-Po	155	200	315	>1200	-20 to +60	3.7	70		-Short calendar life -Low conductivity
NMC	150	300	-	3000	-20 to +55	3.8-4	90-95	-Long cycle and calendar life	-Poor safety
NCA	240	670		500	-20 to +60	3.65	-	-Long cycle and calendar life.	-Poor safety
LEP	130	247	-	3600	-30 to +55	3.3	-	-Good thermal and chemical stability. -High safety. -Low cost	-Low energy density.

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The battery loses capacity not just while cycling, but also during storage or in a dormant state when the battery does not produce power^[34]. In storage circumstances, capacity loss is classified into two forms: reversible due to discharge on their own and irreversible due to variations in temperature, SoC, and storage duration. As excessive temperatures and SoC accelerate the loss of capacity, battery aging is also impacted. The authors in^[35] have conducted tests on LTO and NMC, and found that storing the battery at 60°C or less has no impact on the battery, but at 80°C, it leads to a reduction in capacity because of the strong gassing behavior.

Table 1: Comparison of the most prevalent types of EV batteries^[1,30-33]

There are two expressions to define battery life: cycle life and calendar life. Calendar life is the amount of time left until the battery comes to the EoL during storage; this type of aging increases with time, temperature, and SoC. Cycle life is the number of cycles that a battery can go through during its working process before losing 20% of its initial capacity. According to^[36], lithium-ion battery can achieve 2000 cycles at 20°C, otherwise 800 cycles at 50°C. In^[37], tests on lithium-metal-polymer batteries show that cycling at a low DoD reduces cycle aging and capacity fade.

There are many mechanisms that cause degradation, which vary depending on the anode and cathode materials used. Modes of degradation Lithium-Ion batteries can be identified through the loss of lithium inventory and loss of active material. The former is typically induced through the decay of reusable lithium, which is highly adverse to the achievable capacity of the battery. The loss of active



material is a reduction in the number of lithium intercalation sites because of the aging of the electrodes. The combined effect of LLI and LAM is known as power fade^[38].

3.1. Degradation mechanisms on the anode

The lithiated graphite anode is not stable, therefore, batteries are assembled with lithium ions intercalated in the cathode. In the first cycle, the voltage source is applied to charge the battery, and then the lithium ions transfer to the anode. When lithium ions react with the anode, a thin layer of lithium oxide and lithium carbonate is formed [29]. This layer is known as SEI; when it forms, Liions are irreversibly consumed, decreasing capacity and causing LLI. Nevertheless, a strong SEI film is essential to the anode and overall battery performance, as it prevents any contact between it and the electrolyte, thus avoiding extra side reactions. However, it is hard to control SEI growth^[12].

SEI is supposed to be permeable for positive lithium ions only; however, electrons, solvents, and solvated cations may diffuse to the electrode, resulting in solvent cointercalation. The graphite exfoliate as a result of this, which results in a reduction of active material. Therefore, growing SEI film consumes positive Li-ions, causes capacity fade, and increases internal resistance^[29].

By cycling the battery, the graphite anode volume changes by approximately 10%, leading to a crack in the SEI film and contact between the anode and the electrolyte, which further leads to additional SEI growth. Superficial intercalation of the anode with (+) lithium ions is typically stimulated through retaining full charge of the battery during operation [39]. As a result, it is devised to count for nearly 10% increase in the relative capacity of the anode to mitigate the formation of ion layers on its surface^[40].

However, charging the battery at a high current rate leads to the deposition of lithium ions on the anode surface instead of being intercalated into the anode lattice due to the speed of lithium ions. Therefore, regardless of the designed anode/cathode ratio, the speed of Li ions induces lithium plate formation^[40].

Metallic lithium formation is influenced by operating or idling the battery at a high SoC and cycling the battery at a high DoD^[41]. This process leads to LLI, an increase in internal resistance^[42], and even may destroy the anode structure and separator, resulting in short circuits and thermal runaway. Furthermore, lithium metal can react with electrolyte, resulting in acceleration of the aging process^[43].

3.2. Degradation mechanisms on the cathode

There is a wide diversity in cathode aging, considering that cathode degradation is dependent on its material. LAM is the most common cathode degradation mechanism. When transition metals are dissolved in the electrolyte, it's called" Transition Metal Dissolution" (TMD) and causes the loss of active materials. Furthermore, meager amounts of water can form Hydrofluoric Acid (HF), which also causes the dissolution of the transition metal and consequently leads to capacity fade^[44]. Moreover, TMD can increase the SEI film by being deposited on the anode, leading to a reduction in cathode active material. It is worth noting that TMD occurs, especially for cathodes that contain manganese in their structure^[43].

Because of cathode structure-prone change, lithiation and delithiation of the cathode cause volume change and mechanical stress, resulting in cracks in the materials. Also, a high current or voltage of the cells cycling impacts structural phase transitions in the cathode and causes cathode material fissures. Cracking fractures hinder the transition of lithium ions, causing capacity fade^[45].

The structural changes can expose the cathode to the electrolyte, resulting in LLI and reducing the available active materials in the cathode^[12]. The side reaction between cathodes and electrolytes results in the formation of the Cathode Electrolyte Interface film (CEI), which is smaller than the SEI and more difficult to measure. At high temperatures, metal oxide loses oxygen, and at high voltages, electrolyte decomposes. These two processes cause gas generation, resulting in cracks in cathode materials^[46].

3.3. Degradation mechanisms on the electrolyte

The electrolyte influences the battery's cycle stability, capacity, and safety. It typically contains lithium hexafluorophosphate (LiPF6), which is unstable and easily decomposed into LiF and PF5 and organic solvents. Electrolyte aging occurs due to the reaction between PF5 and organic carbonates. This electrochemical reaction leads to the formation of SEI and CEI films on the surface of the anode and cathode, respectively^[47].

3.4. Degradation mechanisms on inactive materials

Over discharge influences the anode current collector, which leads to copper dissolution. Therefore, if enough copper is dissolved, internal short circuits could occur. On the other hand, overcharge influences the cathode current collector, resulting in aluminum corroding and cell resistance increasing^[46].

Lithium plating, transition metal dissolution, and copper dissolution can cause dendritic growth, which leads to mechanical damage to the separator. Even worse, these dendrites may puncture the separator, causing internal short circuits^[48].

4. KEY-FACTORS INFLUENCING DEGRADATION OF BATTERIES

The previously degradation mechanisms are dependent on cycling and storage conditions besides cell chemistry. These conditions are defined by many variables, such as a change in temperatures, the current rate in cases of charge and discharge, and an alteration in the State of Charge (Δ SoC). Therefore, the factors influencing battery degradation can be categorized into the three main variables mentioned.

4.1. Temperature

Temperature is considered the dominant factor affecting battery degradation rate. Both high and low temperatures accelerate the degradation of Li-ion batteries, as temperature is directly proportional to battery capacity. It also influences the rates of both main and side reactions inside Li-ion batteries. Therefore, the rate of side reaction increases with increasing temperature^[49].

The environment temperature has a significant influence on battery degradation and batterry life, as indicated in many accelerated aging tests. Qian et al.. conducted a study to investigate the effects of temperature variation on the lithium-ion battery cycle. The study concluded that the ambient temperature influences the SEI film growth, as the cathode degradation rate at 45°C is 10 times higher than the rate at 25°C. Also, when the ambient temperature is high, there is a significant capacity loss during the storage of the battery^[50].

If the temperature rises beyond a certain point, it will result in a thermal runaway. Moreover, as it rises, the viscosity of the electrolyte decreases, which leads to obstructing the diffusion of the lithium ions. When it rises above a certain limit, which is often 25°C, the aging rate increases and continues to increase as the temperature increases. Which leads to an increase in the thickness of the SEI film as well.

Additionally, operating the battery at high temperatures accelerates the TMD process on cathode. accelerate when the battery operates at high temperatures Furthermore, temperatures above 60°C result in a severe capacity fade. It gets even worse when the temperature rises higher than

80°C, which leads to the decomposition of the SEI layer, accelerates degradation, and causes thermal runaway^[51].

As mentioned before, low temperatures also accelerate the degradation of Li-ion batteries and leads to additional side reactions. These interactions can reduce the intercalation rates of lithium ions due to the slow Li-ions diffusion into the anode, increasing the strength of the lithium plating on the anode surface. This causes an enduring reduction in active Li-ions. Temperatures below 30°C increase the resistance of the cell. Particularly, charging batteries at low temperatures can result in lithium deposition, angments the degradation process and potentially causing hazardous conditions^[51].

Hannan *et al.*. indicated that the charging range for lithium-ion batteries is between $15 \circ C$ and $50 \circ C^{[42]}$. Pesaran et al.. identify 15 30°C as the optimal temperature range for Li-ion batteries. However, the acceptable range is 20°C to 60°C. According to Li et al.., LiPF6 and LiBF4 batteries' capacities are significantly reduced when the temperature decreases below 20°C, but at 25°C, there is only a $10\%^{[52]}$.

Dubarry et al.. found that LFP batteries tested at 60° C had a five-fold higher internal resistance compared to those tested at 25° C^[53]. A study conducted on NMC batteries demonstrated that the battery lost 7.5% of its capacity when it cycled at 85° C, and 22% at 120°C. Therefore, the key to extending battery life is to make sure that the cycling or storing of the battery is in a suitable temperature range. Figure 3 shows the optimal temperature operating range of LIB with different charging rates. In addition, the aging mechanisms at high and low temperatures are shown in Table 2.

Temperature	Mechanisms		
Low Temperature	 Mechanical deformation of the negative electrode lithium de position. Lithium plating becomes more competitive Reduction in metal ions Damage of the active material's structure. 		
High Temperature	Increase the rate of the inside reactions • Thickened SEI film • Cathode degradation • Increased lithium plating • Failure of the binder		

Table 2: Mechanisms at high and low temperatures

4.2. State of charge (SoC)

SoC is an expression of the present battery capacity as a percentage of its maximum capacity. It strongly influences the aging rate. Therefore, overcharge and overdischarge lead to accelerated battery degradation and shortened battery life. Thermal runways can be induced by over-charging of the battery. Overcharged cells endure irreversible capacity loss and stability changes as well, which can raise the risk of safety issues. On the other side, over dis-charge results in capacity loss and the prospect of safety issues^[54, 55].

Therefore, a higher SoC typically denotes a higher terminal voltage, which indicates a lower anode potential and a higher cathode. Lower voltage causes side reactions, leading to accelerated battery aging^[14].

Accordingly, a combination of high SoC and high



temperature hastens battery degradation^[7]. On the contrary, reducing both in appropriate proportions extends the battery life. However, lowering SoC excessively low has

a negative impact on battery life due to the dis- ordering of the cathode active material structure and corrosion of the anode copper current collector^[5].



Fig. 3: Cycle life in regards to temperature at various charging rates of LIB (based on^[56]).

Amiri *et al.*. deduce that prolonged battery life can be achieved by small changes in SoC during cycling^[57]. Cycles with partial discharge lead to less capacity loss compared to those with full discharge because the accumulated stress from each cycle is a factor in the reduction of battery life^[58]. According to Hoke *et al.*., reducing the aging of LIBs can be achieved by keeping the temperature and discharge rate constant and minimizing the time at high SoC^[59].

Millner identifies procedures to prolong the battery life by avoiding high SoC >60%, DoD

>60%, and high temperatures > $35 \circ C^{[60]}$. However, Marano and Madella show that discharging LIBs at >%25 SoC adversely affects the efficiency and performance of the battery^[61]. In general, 60%–97% is the safest region for a battery, according to Trippe *et al.*.^[62].

In storage conditions, high SoC 80% and high temperatures 45°C lead to the highest capacity degradation rate. Thomas Bank *et al.*. conducted calendar aging tests on LTO and NMC cells at various SoCs, and indicated that during the 300 days calendar life, a higher SoC >70% significantly accelerates battery aging^[35].

To conclude, most literature indicates that storing LIBs at high SoC and high temperatures causes rapid capacity reduction and, as a result, shorter longevity. Low SoC in the storage state, for instance, is around 20% beneficial to battery life and safety; however, 40% SOC in a cool environment is recommended for a long storage period, according to Faria *et al.*., which reduces calendar aging^[55].

4.3. C-rate/ Charging Current

The rate and magnitude of battery charging or depletion plays a central role in accelerating the mechanisms of

capacity loss over time. High C-rate causes irregular distribution of current, resulting in the deposition of metallic lithium and SEI growth. When the battery is discharged at high rates, lithium ions do not fully interact with the cathode, resulting in the formation of lithium dendrite, which causes capacity fade^[63].

If a high charging current is applied to the battery, lithium ions transfer faster to the anode. Consequently, the flow of lithium ions will be higher than the amount that can be intercalated into the electrode^[62].

Additionally, high C-rates also cause a rise in internal temperature and induce side reactions, which lead to loss of active material. When the C-rates exceed a certain level, the increased temperature inside the battery can cause material stress, accelerate capacity loss, and damage the battery^[64].

According to an experimental study conducted by Mussa *et al..*, charging at 3-C caused additional lithium plating, whereas charging at 4-C resulted in gas evolution and graphite exfoliation^[64]. Spingler *et al..* show that capacity fade becomes increasingly evident at high C-rate. Overall, charging or dis-charging at a lower C-rate would extend the battery cycle life^[65].

Figure 4 presents a comprehensive overview of the major mechanisms of the degradation of Li-ion batteries and the associated factors. Table 3 compares the degradation data of various batteries from recent experimental studies. The degradation rate significantly varies based on battery chemistry, testing conditions, and the impact of concurrent degradation variables on the battery. Furthermore, studies have demonstrated the substantial influence of temperature, SoC, and C-rate on the battery degradation rate during both cycling and storage phases.

5. LIFETIME PROLONGATION OF BATTERIES

LIB life extension reduces the need for a new battery, which has a beneficial impact on the environment and the economy. As it leads to lower carbon dioxide (CO2) emissions. In addition, the replacement of LIB has an adverse impact on the economy, as the price of LIB may cost up to 50% of the total price of electric vehicles. To extend the battery's life, it should avoid the variables that accelerate aging in storage and usage conditions. Battery management system (BMS) and users' behavior are responsible for avoiding these variables^[57].

As mentioned before, temperatures, SoC, and C-rate are the variables that affect battery life. Therefore, based on measuring these variables, the BMS can protect Liion batteries from deep overcharge or over-discharge. The primary objectives of BMS are to safeguard battery cells and battery packs from damage, guarantee suitable operating temperature limits, regulate SoC fluctuations across cells, enable reliable use, maximize battery longevity, and maintain battery health^[30].

As known, High temperatures degrade roughly every component of a Li-ion battery, especially with high voltages. Additionally, they can result in serious safety risks because a gas could form inside the battery, increasing the possibility of an explosion. Low temperature cycling makes batteries more vulnerable to lithium plating, which can lead to inner short circuits that permanently harm the battery. Therefore, temperature recommendations are stringent in high and low temperature cases^[49].

Table 3: Experimental investigations on Li-ion battery degradation associated with the main key variables.

Key-facotr	Experimental test	Battery type	Operated conditions	Test results
		NMC/graphite, pouch, 40 Ah	23°C	2600 cycles to reach EoL
	Cycling ^[66]		45∘C	2000 cycles to reach EoL
			65∘C	800 cycles to reach EoL
			25∘C	65+ days to reach EoL
			50∘C	50 days to reach EoL
	$C_{\rm realized at 1} C^{[40]}$		60∘C	35 days to reach EoL
	Cycling at 1 C		70∘C	22 days to reach EoL
			-10°C	10 days to reach EoL
			-20°C	7 days to reach EoL
		 LFP/graphite, 26650, 2.85 Ah 	10°C	loss 3.7% of capacity in 230 days
Temperature			25°C	loss 4.6% of capacity in 230 days
	Stored at 100% SoC ^[67]		35∘C	loss 5% of capacity in 150 days
			45∘C	loss 5.9% of capacity in 100 days
			55°C	loss 7% of capacity in 70 days
			25°C	loss 1% of capacity after 1 year
	Stored at 50% SoC ^[19]		45°C	loss 7% of capacity after 1 year
			60°C	loss 30% of capacity after 1 year



				Loss 18% of the initial
	Cycling ^[68]	LCO/graphite, pouch, 1.5 Ah	0%-100% SoC	capacity after 800 equivalent cycles
			20%-80% SoC	Loss 10% of the initial capacity after 800 equivalent cycles
			40%-100% SoC	Loss 11% of the initial after 750 equivalent cycles
			0%-60% SoC	Loss 3% of the initial capacity after 750 equivalent cycles
		LFP/graphite, 26650,2.85 Ah	100% SoC	Loss 8% of capacity in 235 days
	Stored at $45 \circ C^{[67]}$		75% SoC	Loss 6.2% of capacity in 235 days
	Stored at 45 °C		50% SoC	Loss 5.6% of capacity in 235 days
State of Charge			25% SoC	Loss 4.4% of capacity in 235 days
		LFP/graphite, 18650, 1.06 Ah	100% SoC	Loss 5% of capacity in 10 months
	Stored at 25°C ^[69]		60% SoC	Loss 3% of capacity in 10 months
			30% SoC	Loss 1% of capacity in 10 months
	Stored at 40°C		100% SoC	Loss 12% of capacity in 10 months
			60% SoC	Loss 8% of capacity in 10 months
			30% SoC	Loss 6% of capacity in 10 months
	Stored at 55°C		100% SoC	Loss 25% of capacity in 10 months
			60% SoC	Loss 21% of capacity in 10 months
			30% SoC	Loss 15% of capacity in 10 months
	Cycling ^[70]	NMC + LCO/graphite, 18650, 1.1 Ah	1 A	Reached EoL at 1050 cycles
			3 A	Reached EoL at 1000 cycles
			5 A	Reached EoL at 975 cycles
Charging rate			0.5 C	Reached 85% of initial capacity in 900 cycles
	Cycling ^[71]	LCO/graphite, 18650, 2.4 Ah	1 C	Reached 85% of initial capacity in 630 cycles
			1.2 C	Reached 85% of initial capacity in 500 cycles
			1.5 C	Reached 80% of initial capacity in 300 cycles



Fig. 4: Degradation mechanisms in lithium-ion batteries [72,73].

Considering that a battery's aging process is accelerated by higher SoC, a battery's lifespan can be extended by reducing the amount of time it is exposed to 100% SoC, and this can be achieved by only using a small DoD and charging the battery with the required energy. Therefore, partial charging positively affects the lifetime of the battery, as it approximately doubles the battery lifetime. Moderate SoC alleviates more stress on the battery than high SoC, for instance, cycling the battery at 80%-50% of charge better than 100%-70%^[68].

Fast charging of a battery accelerates its degradation more than standard charging; thus, lower C-rates are beneficial for battery life. Rapidly discharging the battery hastily degrades the battery; however, it can be avoided by choosing a battery with sufficient energy output for the electrified system, limiting sudden starts and stops during driving^[65].

Finally, a list of six recommended behaviors for extending Li-ion battery lifetime is listed below.

1. Reduce exposure to high temperatures during usage and storage.

2. Reduce exposure to low temperatures, specifically in charging mode.

3. Not charge until 100% SoC.

4. Not let the battery exposure 0% SoC.

- 5. Not using fast charging.
- 6. Not storage in high environment temperatures.

6. CONCLUSIONS

In conclusion, electric vehicles EVs and their batteries represent a transformative force in the automotive industry and the broader pursuit of sustainable transportation solutions. The widespread adoption of EVs promises to significantly reduce greenhouse gas emissions, improve air quality, and decrease dependence on finite fossil fuel resources. Which leads to saving the planet from impending disasters caused by global warming and fossil fuel depletion. Central to the success of EVs are advanced battery technologies, especially electrochemical batteries, as they are the most common energy storage devices for their applications. Therefore, lithium-ion batteries are now preferred because of their superior characteristics and performance.

Almost all battery parts, such as the anode, cathode, electrolyte, separator, and current collectors, are exposed to degradation due to multiple and complex mechanisms. The most well-known mechanisms are the formation and growth of the solid electrolyte interphase, the formation of the cathode electrolyte interface, electrolyte oxidation, and lithium plating. The loss of capacity of the battery during a cycle, as well as storage, are also presented. The loss of lithium inventory and the loss of active material could also be classified as degradation modes.

These mechanisms are influenced by various variables that can be summarized into five key points:



High temperatures accelerate internal side reactions; low temperatures lead to reduced metal ions, material damage, and lithium depletion; high SoC or overcharging induces electrolyte decomposition, side reactions with the cathode, and lithium-ion deposition; low SoC or over-discharge causes corrosion of the anode copper current collector and deterioration of the active material's crystal structure; high charge and discharge rates damage the crystal structure of the active material, elevate temperature, and accelerate internal side reactions. These variables underscore the complex interplay of factors influencing Li-ion battery degradation.

ABBREVIATIONS

FV	Electric vehicle
LV	
PHEV	Plug-in Hybrid Electric Vehicles
ICEV	Internal combustion engine vehicles
DoD	Depth of discharge
SEI	Solid electrolyteinterphase
LLI	Loss of lithium inventory
LAM	Loss of active material
TMD	Transition metal dissolution
CEI	Cathode electrolyte interface
BMS	Battery management system

7. REFERENCES

 Yong JY, Ramachandaramurthy VK, Tan KM, *et al.* (2015) A review on the state- of-the-art technologies of electric vehicle, its impacts and prospects. Renewable and Sustainable Energy Reviews 49:365–385. https://doi.org/10.1016/j.rser.2015.04.130
 Morimoto M (2015) Which is the first electric vehicle? Electrical

[2] Morimoto M (2015) Which is the first electric vehicle? Electrical Engineering in Japan 192(2):31–38. https://doi.org/10.1002/eej.22550

[3] Omar N, Verbrugge B, Mulder G, *et al.* (2010) Evaluation of performance characteristics of various lithium-ion batteries for use in BEV application. In: 2010 IEEE Vehicle Power and Propulsion Conference. IEEE, https://doi.org/10.1109/vppc.2010.5729083

[4] Tarascon JM, Armand M (2010) Issues and challenges facing rechargeable lithium bat- teries, Co-Published with Macmillan Publishers Ltd, UK, p 171–179. https://doi.org/10. 1142/9789814317665 0024

[5] Guo R, Lu L, Ouyang M, *et al.* (2016) Mechanism of the entire overdischarge process and overdischarge-induced internal short circuit in lithium-ion batteries. Scientific Reports 6(1). https://doi.org/10.1038/ srep30248

[6] El Ghossein N, Sari A, Venet P, *et al.* (2021) Post-mortem analysis of lithium-ion capacitors after accelerated aging tests. Journal of Energy Storage 33:102039. https://doi.org/10.1016/j.est.2020.102039

[7] Hausbrand R, Cherkashinin G, Ehrenberg H, *et al.* (2015) Fundamental degradation mechanisms of layered oxide li-ion battery cathode materials: Methodology, insights and novel approaches. Materials Science and Engineering: B 192:3–25. https://doi.org/ 10.1016/j.mseb.2014.11.014

[8] Rahman MA, Wang X, Wen C (2013) A review of high energy density lithium-air battery technology. Journal of Applied Electrochemistry 44(1):5–22. https://doi.org/10.1007/s10800-013-0620-8

[9] Ahasan Habib AKM, Motakabber SMA, Ibrahimy MI (2019) A comparative study of electrochemical battery for electric vehicles applications. In: 2019 IEEE Interna- tional Conference on Power, Electrical, and Electronics and Industrial Applications (PEEIACON). IEEE, https://doi.org/10.1109/peeiacon48840.2019.9071955

[10] Wakihara M (2001) Recent developments in lithium ion batteries. Materials Science and Engineering: R: Reports 33(4):109–134. https://doi.org/10.1016/s0927-796x(01) 00030-4

[11] Ding Y, Cano ZP, Yu A, *et al.* (2019) Automotive li-ion batteries: Current status and future perspectives. Electrochemical Energy Reviews 2(1):1–28. https://doi.org/10.1007/s41918-018-0022-z

[12] Woody M, Arbabzadeh M, Lewis GM, *et al.* (2020) Strategies to limit degradation and maximize li-ion battery service lifetime - critical review and guidance for stakeholders. Journal of Energy Storage 28:101231. https://doi.org/10.1016/j.est.2020.101231

[13] Kozakiewicz A, Grzegorczyk T (2021) Electric aircraft propulsion.

Journal of KONBiN 51(4):49–66. https://doi.org/10.2478/jok-2021-0044 [14] Wang L, Chen B, Ma J, *et al.* (2018) Reviving lithium cobalt oxide-based lithium secondary batteries-toward a higher energy density. Chemical Society Reviews 47(17):6505–6602. https://doi.org/10.1039/ c8cs00322j

[15] Depcik C, Cassady T, Collicott B, *et al.* (2020) Comparison of lithium ion batteries, hydrogen fueled combustion engines, and a hydrogen fuel cell in powering a small unmanned aerial vehicle. Energy Conversion and Management 207:112514. https://doi. org/10.1016/j. enconman.2020.112514

[16] Koniak M, Czerepicki A (2017) Selection of the battery pack parameters for an electric vehicle based on performance requirements. IOP Conference Series: Materials Science and Engineering 211:012005. https://doi.org/10.1088/1757-899x/211/1/012005

[17] Miao Y, Hynan P, von Jouanne A, *et al.* (2019) Current li-ion battery technologies in electric vehicles and opportunities for advancements. Energies 12(6):1074. https://doi.org/10.3390/en12061074

[18] Tarascon JM, Recham N, Armand M, *et al.* (2009) Hunting for better li-based electrode materials via low temperature inorganic synthesis. Chemistry of Materials 22(3):724–739. https://doi.org/10.1021/ cm9030478

[19] Wu Sh, Lee PH (2017) Storage fading of a commercial 18650 cell comprised with nmc/lmo cathode and graphite anode. Journal of Power Sources 349:27–36. https://doi.org/10.1016/j.jpowsour.2017.03.002

[20] Zhao C, Yin H, Ma C (2016) Quantitative evaluation of LiFePO4 battery cycle life improvement using ultracapacitors. IEEE Transactions on Power Electronics 31(6):3989–3993. https://doi.org/10.1109/ tpel.2015.2503296

[21] Andre D, Kim SJ, Lamp P, *et al.* (2015) Future generations of cathode materials: an automotive industry perspective. Journal of Materials Chemistry A 3(13):6709–6732. https://doi.org/10.1039/c5ta00361j

[22] Omar N, den Bossche PV, Mulder G, *et al.* (2011) Assessment of performance of lithium iron phosphate oxide, nickel manganese cobalt oxide and nickel cobalt aluminum oxide based cells for using in plugin battery electric vehicle applications. In: 2011 IEEE Vehicle Power and Propulsion Conference. IEEE, https://doi.org/10.1109/vppc.2011. 6043017

[23] Myung ST, Maglia F, Park KJ, *et al.* (2016) Nickel-rich layered cathode materials for automotive lithium-ion batteries: Achievements and perspectives. ACS Energy Letters 2(1):196–223. https://doi.org/10.1021/acsenergylett.6b00594

[24] Zaghib K, Mauger A, Julien C (2015) Rechargeable lithium batteries for energy stor- age in smart grids, Elsevier, p 319–351. https://doi. org/10.1016/b978-1-78242-090-3. 00012-2

[25] Lu J, Chen Z, Ma Z, *et al.* (2016) The role of nanotechnology in the development of battery materials for electric vehicles. Nature Nanotechnology 11(12):1031–1038. https://doi.org/10.1038/ nnano.2016.207

[26] Wright R, Christophersen J, Motloch C, *et al.* (2003) Power fade and capacity fade resulting from cycle-life testing of advanced technology development program lithium- ion batteries. Journal of Power Sources 119–121:865–869. https://doi.org/10.1016/ s0378-7753(03)00190-3

[27] Bloom I, Cole B, Sohn J, *et al.* (2001) An accelerated calendar and cycle life study of li-ion cells. Journal of Power Sources 101(2):238–247. https://doi.org/10.1016/s0378-7753(01)00783-2

[28] Spotnitz R (2003) Simulation of capacity fade in lithium-ion batteries. Journal of Power Sources 113(1):72–80. https://doi.org/10.1016/s0378-7753(02)00490-1

[29] An SJ, Li J, Daniel C, *et al.* (2016) The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling. Carbon 105:52–76. https://doi.org/10.1016/j.carbon.2016.04.008

[30] Hannan MA, Hoque MM, Hussain A, *et al.* (2018) State-of-theart and energy man- agement system of lithium-ion batteries in electric vehicle applications: Issues and recommendations. IEEE Access 6:19362–19378. https://doi.org/10.1109/access.2018. 2817655

[31] Sanguesa JA, Torres-Sanz V, Garrido P, *et al.* (2021) A review on electric vehi- cles: Technologies and challenges. Smart Cities 4(1):372–404. https://doi.org/10.3390/ smartcities4010022

[32] Sun X, Li Z, Wang X, et al. (2019) Technology development of electric vehicles: A review. Energies 13(1):90. https://doi.org/10.3390/en13010090

[33] Un-Noor F, Padmanaban S, Mihet-Popa L, *et al.* (2017) A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development. Energies 10(8):1217. https://doi.org/10.3390/en10081217

[34] Jalkanen K, Karppinen J, Skogstro"m L, et al. (2015) Cycle aging of

commercial NMC/- graphite pouch cells at different temperatures. Applied Energy 154:160–172. https://doi.org/10.1016/j.apenergy.2015.04.110

[35] Bank T, Feldmann J, Klamor S, *et al.* (2020) Extensive aging analysis of high-power lithium titanate oxide batteries: Impact of the passive electrode effect. Journal of Power Sources 473:228566. https:// doi.org/10.1016/j.jpowsour.2020.228566

[36] Tarascon JM, Gozdz A, Schmutz C, *et al.* (1996) Performance of Bellcore's plastic rechargeable Li-ion batteries. Solid State Ionics 86-88:49–54. https://doi.org/10.1016/0167-2738(96)00330-X

[37] Guena T, Leblanc P (2006) How depth of discharge affects the cycle life of lithium- metal-polymer batteries. In: INTELEC 06 - Twenty-Eighth International Telecommuni- cations Energy Conference. IEEE, https://doi.org/10.1109/intlec.2006.251641

[38] Han X, Ouyang M, Lu L, *et al.* (2014) A comparative study of commercial lithium ion battery cycle life in electrical vehicle: Aging mechanism identification. Journal of Power Sources 251:38–54. https://doi.org/10.1016/j.jpowsour.2013.11.029

[39] Agubra V, Fergus J (2013) Lithium ion battery anode aging mechanisms. Materials 6(4):1310–1325. https://doi.org/10.3390/ma6041310

[40] Waldmann T, Hogg BI, Wohlfahrt-Mehrens M (2018) Li plating as unwanted side reac- tion in commercial li-ion cells – a review. Journal of Power Sources 384:107–124. https://doi.org/10.1016/j. jpowsour.2018.02.063

[41] Yan C, Cheng XB, Tian Y, *et al.* (2018) Dual-layered film protected lithium metal anode to enable dendrite-free lithium deposition. Advanced Materials 30(25):1707629. https://doi.org/10.1002/adma.201707629

[42] Hannan M, Lipu M, Hussain A, *et al.* (2017) A review of lithiumion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendations. Renewable and Sustainable Energy Reviews 78:834–854. https://doi.org/10.1016/j. rser.2017.05.001

[43] Vetter J, Nova'k P, Wagner M, et al. (2005) Ageing mechanisms in lithium-ion batteries. Journal of Power Sources 147(1-2):269–281. https://doi.org/10.1016/j.jpowsour.2005. 01.006

[44] Hemmelmann H, Dinter JK, Elm MT (2021) Thin film NCM cathodes as model sys- tems to assess the influence of coating layers on the electrochemical performance of lithium ion batteries. Advanced Materials Interfaces 8(9):2002074. https://doi.org/10. 1002/admi.202002074

[45] Guo J, Li Y, Chen Y, et al. (2019) Stable interface co3o4-coated LiNi0.5mn1.5o4 for lithium-ion batteries. Journal of Alloys and Compounds 811:152031. https://doi.org/10.1016/j.jallcom.2019.152031
[46] Hendricks C, Williard N, Mathew S, et al. (2015) A failure modes, mechanisms, and effects analysis (FMMEA) of lithium-ion batteries. Journal of Power Sources 297:113–120. https://doi.org/10.1016/j. jpowsour.2015.07.100

[47] Horsthemke F, Leißing M, Winkler V, *et al.* (2020) Development of a lithium ion cell enabling in situ analyses of the electrolyte using gas chromatographic techniques.Electrochimica Acta 338:135894. https://doi.org/10.1016/j.electacta.2020.135894

[48] Wang Q, Mao B, Stoliarov SI, *et al.* (2019) A review of lithium ion battery failure mechanisms and fire prevention strategies. Progress in Energy and Combustion Science 73:95–131. https://doi.org/10.1016/j. pecs.2019.03.002

[49] Han X, Lu L, Zheng Y, *et al.* (2019) A review on the key issues of the lithium ion battery degradation among the whole life cycle. eTransportation 1:100005. https://doi.org/10.1016/j.etran.2019.100005

[50] Qian K, Zhou C, Yuan Y, *et al.* (2010) Temperature effect on electric vehicle battery cycle life in vehicle-to-grid applications. In: CICED 2010 Proceedings, pp 1–6

[51] Waldmann T, Wilka M, Kasper M, *et al.* (2014) Temperature dependent ageing mech- anisms in lithium-ion batteries – a post-mortem study. Journal of Power Sources 262:129–135. https://doi.org/10.1016/j. jpowsour.2014.03.112

[52] Pesaran A, Santhanagopalan S, Kim G (2013) Addressing the impact of temperature extremes on large format li-ion batteries for vehicle applications (presentation). Tech. rep., National Renewable Energy Lab. (NREL), Golden, CO (United States)

[53] Dubarry M, Liaw BY, Chen MS, *et al.* (2011) Identifying battery aging mechanisms in large format li ion cells. Journal of Power Sources 196(7):3420–3425. https://doi.org/ 10.1016/j.jpowsour.2010.07.029

[54] Ambrose H, Kendall A (2016) Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility. Transportation Research Part D: Transport and Environment 47:182–194. https://doi.org/10.1016/j.trd.2016.05.009

[55] Faria R, Marques P, Garcia R, et al. (2014) Primary and secondary

use of electric mobil- ity batteries from a life cycle perspective. Journal of Power Sources 262:169–177. https://doi.org/10.1016/j. jpowsour.2014.03.092

[56] Asakura K, Shimomura M, Shodai T (2003) Study of life evaluation methods for li-ion batteries for backup applications. Journal of Power Sources 119-121:902–905. https://doi.org/10.1016/s0378-7753(03)00208-8

[57] Amiri M, Esfahanian M, Hairi-Yazdi MR, *et al.* (2009) Minimization of power losses in hybrid electric vehicles in view of the prolonging of battery life. Journal of Power Sources 190(2):372–379. https://doi.org/10.1016/j.jpowsour.2009.01.072

[58] Xu B, Oudalov A, Ulbig A, *et al.* (2018) Modeling of lithium-ion battery degradation for cell life assessment. IEEE Transactions on Smart Grid 9(2):1131–1140. https://doi.org/ 10.1109/tsg.2016.2578950

[59] Horsthemke F, Leißing M, Winkler V, *et al.* (2020) Development of a lithium ion cell enabling in situ analyses of the electrolyte using gas chromatographic techniques.Electrochimica Acta 338:135894. https://doi.org/10.1016/j.electacta.2020.135894

[60] Millner A (2010) Modeling lithium ion battery degradation in electric vehicles. In: 2010 IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply. IEEE, https://doi.org/10.1109/ citres.2010.5619782

[61] Marano V, Onori S, Guezennec Y, *et al.* (2009) Lithium-ion batteries life estimation for plug-in hybrid electric vehicles. In: 2009 IEEE Vehicle Power and Propulsion Conference. IEEE, https://doi.org/10.1109/vppc.2009.5289803

[62] Trippe AE, Arunachala R, Massier T, *et al.* (2014) Charging optimization of battery electric vehicles including cycle battery aging. In: IEEE PES Innovative Smart Grid Technologies, Europe. IEEE, https://doi.org/10.1109/isgteurope.2014.7028735

[63] Groot J, Świerczynski M, Stan AI, et al. (2015) On the complex ageing characteristics of high-power LiFePO4/graphite battery cells cycled with high charge and discharge cur- rents. Journal of Power Sources 286:475–487. https://doi.org/10.1016/j.jpowsour.2015. 04.001 [64] Mussa AS, Liivat A, Marzano F, et al. (2019) Fast-charging effects on

[64] Mussa AS, Liivat A, Marzano F, *et al.* (2019) Fast-charging effects on ageing for energy- optimized automotive LiNi1/3mn1/3co1/3o2/graphite prismatic lithium-ion cells. Jour- nal of Power Sources 422:175–184. https://doi.org/10.1016/j.jpowsour.2019.02.095

[65] Spingler FB, Wittmann W, Sturm J, *et al.* (2018) Optimum fast charging of lithium- ion pouch cells based on local volume expansion criteria. Journal of Power Sources 393:152–160. https://doi.org/10.1016/j. jpowsour.2018.04.095

[66] Jalkanen K, Karppinen J, Skogstro"m L, *et al.* (2015) Cycle aging of commercial NMC/- graphite pouch cells at different temperatures. Applied Energy 154:160–172. https://doi.org/10.1016/j.apenergy.2015.04.110

[67] Schinpe M, von Kuepach ME, Naumann M, et al. (2018) Comprehensive modeling of temperature-dependent degradation mechanisms in lithium iron phosphate batteries. Journal of The Electrochemical Society 165(2):A181–A193. https://doi.org/10.1149/2. 1181714jes, URL http://dx.doi.org/10.1149/2.1181714jes

[68] Saxena S, Hendricks C, Pecht M (2016) Cycle life testing and modeling of graphite/licoo2 cells under different state of charge ranges. Journal of Power Sources 327:394–400. https://doi.org/10.1016/j. jpowsour.2016.07.057

[69] Zheng Y, He YB, Qian K, *et al.* (2015) Effects of state of charge on the degradation of lifepo4/graphite batteries during accelerated storage test. Journal of Alloys and Com- pounds 639:406–414. https:// doi.org/10.1016/j.jallcom.2015.03.169, URL http://dx.doi. org/10.1016/j. jallcom.2015.03.169

[70] Keil P, Jossen A (2016) Charging protocols for lithium-ion batteries and their impact on cycle life—an experimental study with different 18650 high-power cells. Journal of Energy Storage 6:125–141. https:// doi.org/10.1016/j.est.2016.02.005, URL http://dx. doi.org/10.1016/j. est.2016.02.005

[71] Gao Y, Jiang J, Zhang C, *et al.* (2017) Lithium-ion battery aging mechanisms and life model under different charging stresses. Journal of Power Sources 356:103–114. https://doi.org/10.1016/j. jpowsour. 2017.04.084, URL http://dx.doi.org/10.1016/j.jpowsour. 2017.04.084

[72] Han X, Lu L, Zheng Y, *et al.* (2019) A review on the key issues of the lithium ion battery degradation among the whole life cycle. ETransportation 1:100005

[73] Woody M, Arbabzadeh M, Lewis GM, *et al.* (2020) Strategies to limit degradation and maximize li-ion battery service lifetime-critical review and guidance for stakeholders. Journal of Energy Storage 28:101231