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Strategies to limit degradation and maximize Li-ion battery service lifetime - Critical review and guidance for stakeholders

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ABSTRACT

The relationship between battery operation and their degradation and service life is complex and not well synthesized or communicated. There is a resulting lack of awareness about best practices that influence service life and degradation. Battery degradation causes premature replacement or product retirement, resulting in environmental burdens from producing and processing new battery materials, as well as early end-of-life burdens. It also imposes a significant cost on the user, as batteries can contribute to over 25% of the product cost for consumer electronics, over 35% for electric vehicles, and over 50% for power tools. We review and present mechanisms, methods, and guidelines focused on preserving battery health and limiting degradation. The review includes academic literature as well as reports and information published by industry. The goal is to provide practical guidance, metrics, and methods to improve environmental performance of battery systems used in electronics (i.e., cellphones and laptops), vehicles, and cordless power tools to ultimately better inform users as well as battery designers, suppliers, vehicle and device manufacturers, and material recovery and recycling organizations.

1. Introduction

Lithium-ion batteries (LIBs) are currently the most widely applied technology for mobile energy storage, and are commonly used in cellphones, computers, power tools, and electric vehicles (EVs). Battery degradation occurs both over time (calendar aging) and with use (cycling aging), and is related to battery chemistry, environmental conditions, and use patterns. Limiting degradation has been identified as one of the green principles for responsible battery management [1], as extending battery lifetime decreases costs and environmental burdens associated with the production of new batteries, including material consumption, mining impacts, and greenhouse gas (GHG) emissions [2]. As the mobile electronics and EV industries continue to grow [3], even small improvements in lifetime extension will have significant environmental benefits. Understanding the operating principles and degradation mechanisms of LIBs helps elucidate behaviors that can extend battery lifetime. From this review of academic literature, these degradation mechanisms and relevant variables are identified. These variables are then compared with user guides, user manuals, and publicly available battery information provided by manufacturers, highlighting areas of agreement and disagreement. Finally, through the distillation of these sources, we develop and present a list of best practices for battery lifetime extension.

The remainder of Section 1 describes the operation of and most common materials used in LIBs. Section 2 shows mechanisms by which LIBs degrade and Section 3 illustrates the impact different conditions or variables have on degradation. In Section 4, information provided by companies about battery degradation is reviewed. Section 5 details how degradation is managed, by battery management systems (BMSs), and by users. Here the information in previous sections is synthesized to create a list of best practices for battery lifetime extension. This list is intended to guide users and is presented alongside information showing that currently users either do not know or do not follow many of the behaviors that can extend battery lifetime. Educating the public on these best practices is a primary motivation for this work.

A battery cell consists of positive and negative electrodes and an electrolyte that reacts with each electrode. When a battery is discharging, the negative electrode (anode) is oxidized by the electrolyte, freeing electrons from the anode material. Electrons from the anode flow through an external circuit powering a device, to the positive

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Glossary

LIB	Lithium-ion Battery
EV	Electric Vehicle
GHG	Greenhouse Gas
BMS	Battery Management System
MO_z	Metal Oxide
PP	Polypropylene
PE	Polyethylene
LCO	Lithium Cobalt Oxide
LMO	Lithium Manganese Oxide
LFP	Lithium Iron Phosphate
NCA	Lithium Nickel Cobalt Aluminum Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
LTO	Lithium Titanate
PVDF	Polyvinylidene Fluoride
$LiPF_6$	Lithium Hexafluorophosphate
$LiBF_4$	Lithium Tetrafluoroborate
$LiAsF_6$	Lithium Hexafluoroarsenate
$LiClO_4$	Lithium Perchlorate
EC	Ethylene Carbonate
PC	Propylene Carbonate
DMC	Dimethyl Carbonate
DEC	Diethyl Carbonate
EMC	Ethylmethyl Carbonate
C	Carbon (graphite)
SBR	Styrene-Butadiene Rubber
EoL	End of Life
DoD	Depth of Discharge
AFM	Atomic Force Microscopy
EIS	Electrochemical Impedance Spectroscopy
FIB-SEM	Focused Ion Beam Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
TEM	Transmission Electron Microscopy
XRD	X-Ray Diffraction
LLI	Loss of Lithium Inventory
LAM	Loss of Active Material
SEI	Solid Electrolyte Interphase
TMD	Transition Metal Dissolution
HF	Hydrofluoric Acid
SoC	State of Charge
ΔSoC	Change in State of Charge
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
CO_2e	Carbon Dioxide Equivalent
SoH	State of Health
SoF	State of Function
SoS	State of Safety

electrode (cathode). At the cathode, the metal oxide is reduced, gaining electrons from the external circuit. Charge is conserved at both electrodes by the flow of lithium ions from the anode to the cathode. These ions intercalate into the lattice of each electrode. The electrolyte is ionically conductive but insulating to the flow of electrons, to ensure the electrons flow through the external circuit, preventing self-discharge. A porous separator physically separates the positive and negative electrodes to prevent short circuits, while allowing the flow of ions. This process is shown in Fig. 1. To charge the battery, a voltage is applied to the circuit, and the process moves in the opposite direction.

Material choice is a key variable in battery cost, performance, and function, and a variety of materials are currently used. The positive current collector is typically aluminum coated with cathode material. The negative current collector is typically copper coated with anode material. The separator is typically a polyolefin plastic, such as polypropylene (PP) or polyethylene (PE), though ceramic blends have also been used [4,5].

The cathode is typically a metal oxide. The choice of cathode material, along with anode material choices, will impact nominal voltage, cycle life, self-discharge rate, specific energy, specific power, energy density, power density, operating temperature range, and cost [6]. Commercially available cathodes are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide (NCA), and lithium nickel manganese cobalt oxide (NMC), and composite blends of these materials [7,8].

Anodes are typically some form of carbon, usually graphite. One emerging anode material is lithium titanate (LTO). Compared to carbon anodes, LTO has low energy density but high power density. Though it is currently a more expensive option, it has a higher cycle life and can operate at lower temperatures than traditional carbon anodes [7]. Lithium metal alloys, including lithium-tin and lithium-silicon, have a much higher theoretical capacity than graphite, but large volume changes when cycling have impeded commercialization of these technologies [9].

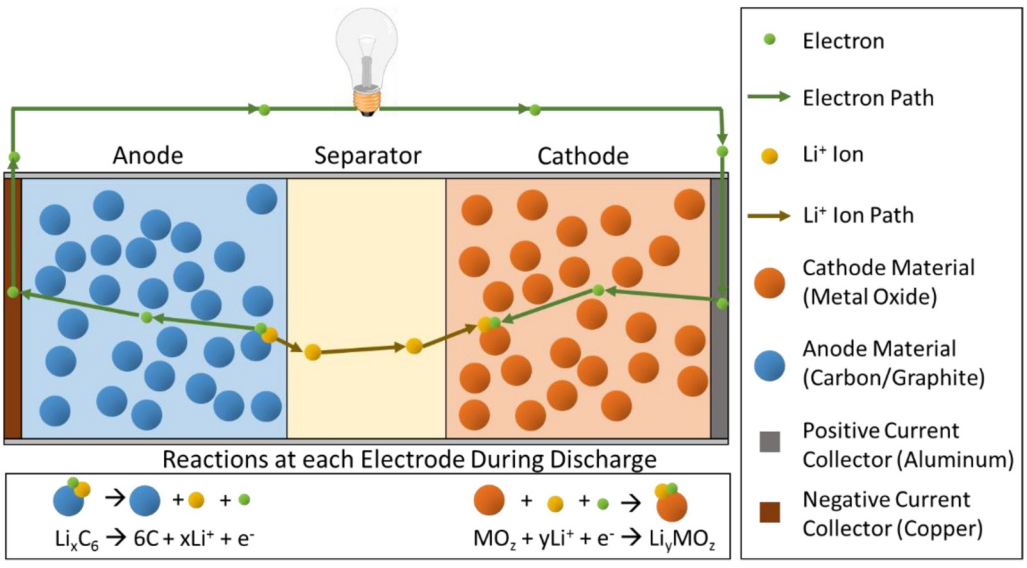

Fig. 1. Flow of electrons and lithium ions and reactions at each electrode during battery discharge. As the battery discharges, Li in the anode (x) decreases and Li in the cathode (y) increases. X corresponds to the battery state of charge and the relationship between x and y depends on the ratio of active material between anode and cathode. Different metal oxides (MO_z) are used as cathode material.

A binder such as polyvinylidene fluoride (PVDF) is used to bind the particles within each electrode to a conductive additive, ensuring the entire electrode is conductive [10]. The cathode and anode are immersed in a gel or liquid electrolyte, consisting of a lithium salt dissolved in a mixture of organic solvents. The most common lithium salt is lithium hexafluorophosphate ($LiPF_6$), though lithium tetrafluoroborate ($LiBF_4$), lithium hexafluoroarsenate ($LiAsF_6$), and lithium perchlorate ($LiClO_4$) have been used [11]. Common solvent mixtures include ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC), diethyl carbonate (DEC), and ethylmethyl carbonate (EMC) [12]. Cathode, anode, and electrolyte materials are all active areas of research, with battery lifetime as one of many performance metrics that can be improved [13]. The most common commercially available battery materials are shown in Table 1.

2. Lithium-ion battery degradation

2.1. Characterization

There are two main forms of battery degradation: capacity fade and power fade. Capacity fade is a decrease in the amount of energy a battery can store. It is measured as a battery's capacity (amp-hours) relative to when the battery was new, expressed as a percentage. For most products, 20% capacity fade (80% of initial battery capacity) is considered the battery's end of life (EoL) [14]. The rate of capacity loss is significantly dependent on charging/discharging conditions, including maximum voltage, depth of discharge (DoD), current and load profiles, and temperature [15]. Power fade is a decrease in the amount of power a battery can provide due to an increase in the battery's internal impedance (resistance - measured in ohms). Capacity fade and power fade can occur simultaneously. To understand the precise mechanisms that lead to these forms of degradation, both in-situ (including in-operando) and ex-situ (post-mortem) characterization techniques are used [16]. These include atomic force microscopy (AFM) [17], electrochemical impedance spectroscopy (EIS) [18], focused ion beam scanning electron microscopy (FIB-SEM) [19,20], Fourier transform infrared spectroscopy (FTIR) [21], Raman spectroscopy [22], transmission electron microscopy (TEM) [23], X-ray diffraction (XRD) [24], and a wide range of combinations of these methods and emerging techniques [25].

2.2. Modes and mechanisms

The aging mechanism and cycle life depend on the battery's cathode and anode material [26]. Battery degradation is complex, as different factors from environmental conditions to product utilization patterns interact to generate different aging effects [27]. Degradation can also take place during rest periods, when energy is not being drawn from the battery [28].

The major degradation modes in LIBs are loss of lithium inventory (LLI) and loss of active material (LAM) [26]. Loss of lithium inventory is a decrease in the amount of cyclable lithium in the battery. As lithium is consumed in side reactions, it is no longer available to intercalate into the electrodes, decreasing battery capacity. Loss of active material results from degradation of electrodes, reducing the number of sites available for lithium intercalation. This leads to both capacity fade and power fade, and occurs at both the anode and cathode [29]. Capacity fade from LLI and from LAM are not additive; the overall degradation is a function of the dominant mechanism. Conversely, power fade is the summation of the impact from LLI and LAM [30].

Degradation impacts every part of a battery. In addition to the active materials, inactive components (e.g., binder, current collectors, separator) all degrade with time and use. There are many processes contributing to the degradation of each component, and it is a challenge to study these processes individually, as they occur on similar time scales and interact with one another [31]. Nevertheless, there have been many experimental studies on each of these degradation processes, focusing on both mechanisms by which they degrade the battery, and variables that influence the degradation.

2.2.1. Anode degradation

The major mechanisms for anode degradation are solid electrolyte interphase (SEI) formation, metallic lithium plating, and loss of active material. Batteries are assembled in a discharged state, since lithiated carbon is not stable in air [32]. Therefore all of the lithium ions are initially in the electrolyte or intercalated in the cathode [33]. When the battery is cycled for the first time, lithium ions from the cathode along with organic compounds from the electrolyte solvent react with the graphite anode creating a thin film called the SEI [33]. The creation of the SEI irreversibly consumes lithium, decreasing the lithium inventory available for cycling, and reducing battery capacity [34]. SEI formation happens during the first several cycles coating the graphite electrode with a film tens to hundreds of angstroms thick [32]. This film consists of organic salts, inorganic salts, and trapped gas molecules [35]. Approximately 10% of the initial capacity is irreversibly consumed in SEI formation [33]. Ideally, once the SEI is created, the graphite electrode is fully coated and the reaction cannot continue. The SEI protects the anode from further reacting with the solvent, is electrically insulating, and has high selective permeability for lithium ions. A robust SEI layer is critical to good battery performance. However, SEI growth is difficult to control because it is highly dependent on the type of graphite, graphite morphology, electrolyte composition and concentration, electrochemical conditions, and cell temperature [33].

The SEI slowly corrodes with time. SEI dissolution exposes the graphite to the electrolyte, leading to additional SEI growth and thus additional capacity loss [34]. Increased temperature increases the dissolution rate, and at high temperatures, increasing voltage becomes a significant factor as well [36]. The ideal SEI is only permeable for Li^+ cations, however anions, electrons, solvated cations, solvents, and impurities can diffuse through the SEI to the electrode [31]. This can result in solvent co-intercalation, creating mechanical stress within the electrode lattice. Also, electrolyte reduction within the electrode can create gases which will increase pressure and stress [31,32]. When the battery is cycled and the graphite structure is lithiated and de-lithiated, its volume expands and contracts by approximately 10% [37]. The mechanical stresses created by each of these mechanisms can lead to graphite exfoliation via particle cracking. This will decrease the amount of available active material, as well as creating additional sites for SEI growth. Lastly, these stresses can fracture and isolate electrode particles from the bulk of the material, further reducing the available active material.

When a battery is at a high SoC, the anode is highly lithiated and the

Table 1
Common materials used in Li-ion batteries.

Cathode	Anode	Electrolyte Salt	Electrolyte Solvent	Separator	Binder	Current Collectors	Conductive Additives
LCO	C	$LiPF_6$	EC	PP	PVDF	Al (cathode)	black carbon
LMO	LTO	$LiBF_4$	DMC	PE	SBR	Cu (anode)	
LFP		$LiAsF_6$	DEC	ceramics		Al (LTO anode)	
NCA		$LiClO_4$	EMC				
NMC			PC				

potential at the anode is low [38]. If the potential at the anode surface is below 0 V vs Li/Li$^+$, lithium deposition on the anode becomes thermodynamically possible. At such potentials, some lithium ions will be deposited on the surface of the electrode as metallic lithium rather than intercalated into the anode during charging [39]. To help prevent such lithium deposition, batteries are typically designed with 10% higher anode capacity than cathode capacity (N/P ratio > 1.1), so the anode is never fully lithiated [39]. Despite this precaution, lithium plating from overcharge can still occur if the initial mass ratio of lithium is higher than expected (N/P lower than expected), or if the initial LLI due to SEI growth was smaller than expected [11]. Even with properly designed ratios, high charge rates can induce lithium plating if the charge rate is greater than the rate of lithium diffusion into the graphite [29]. Low temperatures slow ion diffusion in the anode and/or the electrolyte, allowing more lithium plating and dendrite growth to occur [31]. Deposited lithium forms its own SEI layer, leading to further LLI and increased internal resistance [28,40–42].

When lithium ions are de-intercaled during discharge, metallic

Fig. 2. Degradation mechanisms in Li-ion batteries.

lithium is stripped from the anode. If electrical contact between lithium and the anode is lost, this lithium becomes “dead lithium” and is a source of capacity loss [39]. SEI can form on this dead lithium, which is an additional capacity loss mechanism [39].

2.2.2. Cathode degradation

There is greater variation in cathode degradation, since cathode aging is highly material dependent and there is a wider variety of cathode chemistries currently in use [31]. Major cathode degradation mechanisms include loss of active material and SEI growth.

Loss of active material can occur when transition metals (Ni, Mn, Co, Fe) in the cathode dissolve in the electrolyte [43], in a process aptly named transition metal dissolution (TMD). This is accelerated at high temperatures. Additionally, trace amounts of water in the battery can undergo hydrolysis with the $LiPF_6$ salt to form hydrofluoric acid (HF), which will cause TMD [42]. Finally, TMD can occur when the electrode is fully discharged, most significantly for cathodes containing manganese [31]. The dissolved transition metals can then deposit on the anode SEI, increasing conductivity and leading to additional SEI growth [42,43], as well as forming dendrites and decreasing the available active cathode material [31].

Like the anode, the cathode has an SEI layer, though it is much smaller than the anode layer due to the high voltage at the cathode, and is harder to measure and characterize [44,45]. Exposing the cathode to the electrolyte results in loss of lithium inventory as the cathode and electrolyte react. Lithiation and delithiation lead to volume changes and mechanical stress, which can cause cracking, creating additional reaction sites. Unlike the anode, inhomogeneous lithiation can also induce structural phase transitions in the cathode structure, such as Jahn-Teller distortion, further reducing the amount of lithium ions the cathode can accept [31]. Low state of charge (SoC) can increase this effect, but various dopants can be used to stabilize the structure [31]. These structural changes can decrease the available active material in the cathode, as well as expose the cathode to the electrolyte.

Cracking can also be caused by gas generation. This can come from oxygen loss from the metal oxide at high temperatures, or from electrolyte decomposition at high voltages [11,42]. Overcharge can also cause point defects in the lattice where oxygen or transition metals take the spaces in the structure where lithium would otherwise be intercalated [46].

At elevated temperatures (150 °C to 310 °C depending on the material), the cathode itself can decompose, leading to loss of active material, releasing of gas, and thermal runaway [46].

2.2.3. Inactive material degradation

Inactive battery components, including the binder, current collectors, and separator, are also subject to degradation. Binder materials can decompose at elevated temperatures or voltages. These materials can also react with the charged anode forming products like LiF, increasing mechanical stress. The current collectors can corrode if they come in contact with the electrolyte, reducing their conductivity, leading to power fade [31]. The anode current collector is vulnerable to overdischarge, which can lead to copper dissolution resulting in free copper particles suspended in the electrolyte. Internal short circuits can occur if enough copper is dissolved and copper dendrites grow [44]. The cathode current collector is vulnerable to overcharge, leading to pitting corrosion of the aluminum. This increases cell impedance, but unlike copper dissolution will not lead to catastrophic failures [44]. The separator is vulnerable to mechanical damage from dendritic growth. Dendrites could form because of lithium plating, transition metal dissolution, or copper dissolution from the current collector. These dendrites can puncture the separator and lead to internal short circuits [44]. Internal short circuits may also be caused by the separator material melting at high temperatures or tearing due to mechanical damage. Regardless of cause, internal short circuits can lead to thermal runaway, fires, and explosions [47]. Finally, mechanical or electronic contact loss between many of a battery's components can lead to higher cell impedance and power fade. Contact loss between particles in each electrode has already been discussed, but there can also be contact loss between electrodes and binders, binders and current collectors, and electrodes and current collectors [31]. A summary of major degradation mechanisms and their related conditions is presented in Fig. 2.

2.2.4. Higher order degradation

All the degradation mechanisms mentioned in Sections 2.2.1–2.2.3 occur at the individual cell level. There are also degradation mechanisms external to the cell that could affect the terminals or casing. Additionally, for any battery with more than one cell, there are battery pack dynamics and pack level degradation to account for. If cells in a module or pack are not balanced, they are vulnerable to overcharge, overdischarge, and overheating [48]. Active and passive balancing techniques are used by the BMS, yet as shown by Zheng et al., pack capacity will always fade more critically than cell capacity. Battery packs therefore always have a shorter lifetime than their individual cells [49]. This is primarily explained by unavoidable differences between cells due to inconsistent manufacturing or different operating and environmental conditions [49].

3. Key degradation variables

The aging process can lead to increased self-discharge rate and resistance as well as reduced capacity [28,50]. The various degradation mechanisms cited in Section 2 depend on complex and interacting mechanisms relating to cell chemistry and storage as well as charging and discharging conditions such as temperature, cycle depth, frequency of cycling, change in state of charge (ΔSoC), charge and discharge current magnitude, and elevated voltage exposure [27,51]. Battery degradation has a large impact on product performance. In EVs, for example, capacity fade influences range capability and fuel consumption, while power fade impacts driving performance, including acceleration, gradeability, and maximum charging rate during regenerative braking or charging [52,53]. In addition to factors such as the temperature distribution within the battery, DoD, SoC, and driving and charging conditions, the user's demands for power and energy also determine the operating conditions of the battery and the stress factors that influence the rate of aging [52,54]. The variables impacting degradation can be put into three main categories: temperature, state of charge, and current (C-rate) [55].

3.1. Temperature

Many studies have demonstrated the impact of temperature on LIBs both in storage and while in use. In an examination of two LFP batteries, Dubarry et al. show that the resistance of a battery tested at 60 °C was five times greater than the battery operated at 25 °C [56]. Hannan et al. argue that LIBs should be charged between 15 °C and 50 °C [41]. In another study, Pesaran et al. define 15–35 °C as the desired operating temperature for LIBs in PHEVs. They also show that lower battery degradation rate enables a smaller and lower cost battery [57].

Smith et al. apply a semi-empirical model of NCA/graphite chemistry in PHEVs to investigate calendar aging in various environments with different ambient temperatures and solar radiation [58]. Their modeling shows a two year difference in battery lifetime between the ambient temperature model and ambient plus solar radiation model in Phoenix, AZ, showing the large impact of parking in the sun or the shade.

Serrao et al. show that temperatures above 25 °C accelerated battery aging in Hybrid Electric Vehicles (HEVs) [59]. Hatzell et al. conclude that temperatures below -30 °C led to considerably increased cell impedance, temperatures above 60 °C led to severe capacity loss, and at temperatures above 85 °C the SEI layer decomposed, which can cause rapid degradation and thermal runaway [60]. Ramadass et al. cycled

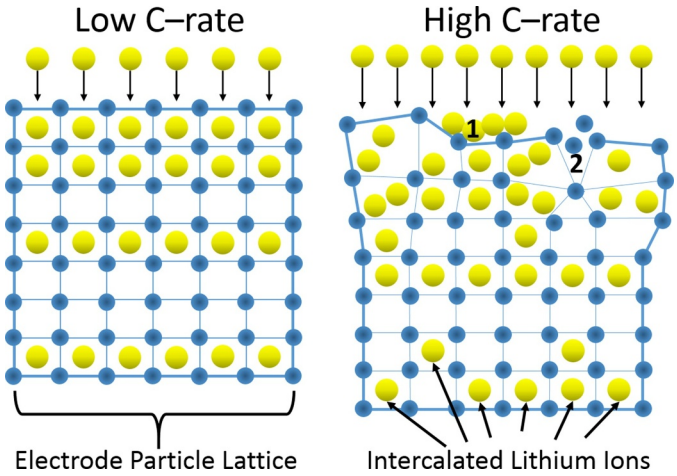

Fig. 3. Comparison between a low charging/discharging current and a high discharging/charging current, showing 1) lithium plating, and 2) particle cracking.

Sony 18650 LCO cells, revealing that cells at 25 °C and 45 °C lost about 31% and 36% of their initial capacity after 800 cycles, while cells at 50 °C lost more than 60% capacity after 600 cycles and cells at 55 °C lost 70% after 500 cycles [61]. Ren et al. show that the temperature at which thermal runaway begins also varies with the battery cell configuration and pressure relief design [62].

3.2. State of charge

Overcharge, overdischarge, and high depth of discharge lead to the fast decay of battery life [28,50,63]. Overcharge is one of the most serious problems, and can result in thermal runaway because external energy is being directly added into the battery. On the other hand, overdischarged cells experience irreversible capacity loss and changes in stability, which can affect tolerance to abuse conditions and increase the likelihood of safety issues [50]. Also, the coupling of high SoC and high temperature accelerates degradation [27]. Faria et al. recommend a cool environment with SoC around 40% to reduce the calendar aging during a long storage period [28]. They also argue that partial discharge cycles result in lower capacity loss than full discharge cycles. Capacity fade in LIBs as a result of cycling resembles the fatigue of materials subjected to cyclic loading. The accumulated stress of each cycle contributes to the loss of battery lifetime [64].

Zhang et al. show that a typical laptop battery stored at 25 °C and 100% SoC will irreversibly lose 20% of its capacity each year [15].

Ortega-Vazquez shows that the impact of cycling characteristics also depends on battery chemistry. For example, the capacity of LFP batteries is sensitive to the total number of cycles that the battery undergoes, while NCA batteries are sensitive to the total number of cycles and to the DoD of the cycles [65].

Amiri et al. conclude that smaller changes in SoC during cycling increases battery lifetime [66]. Millner specifies that the battery lifetime can be kept in an acceptable range for Plug-in Hybrid Electric Vehicles (PHEVs) by avoiding deep cycles (>60% DoD), high temperatures (>35 °C), and high average SoC(>60%) [67]. Marano and Madella show that to reach 10 year/150,000 mile PHEV lifetime, overcharging and operation above 95% SoC should be avoided. They also show efficiency and performance degradation if LIBs are discharged or operated at lower than ~25% SoC [54].

Hoke et al. argue that if battery temperature and charge-discharge cycling are kept constant, minimizing time spent at high SoC minimizes degradation [68]. If the next day's energy requirement is known, the battery can be charged to the minimum required level, rather than to the conventional full charge [68]. Trippe et al. define 60% to 97% SoC as the safe window to preserve battery health [40].

Lunz et al. show that battery lifetime can be increased by reducing the target SoC to lower values, or by minimizing rest periods at high SoC. Therefore, battery charging should occur immediately before departure [69]. Because standby times dominate battery operation, there is a large opportunity to increase battery lifetime by adjusting the time and frequency of charging (smart charging).

For PHEV batteries, Smith et al. suggest several strategies to reduce calendar aging from high SoC. These include reducing time spent at high SoC by just-in-time (delayed) charging, and intentional partial-depletion of the battery from vehicles parked in hot environments (e.g., by running the cooling system) until an appropriate SoC is reached [58].

3.3. C-rate

In addition to temperature and DoD/SoC, battery aging also depends on accumulated charge transfer in and out of the battery (amp-hour throughput), and the current magnitude relative to battery size (C-rate) [54]. Higher charging and discharging current rates can accelerate cell degradation due to an uneven distribution of current, temperature, and material stress, where Li-ion intercalation and diffusion speed are the limiting factors. These unevenly distributed conditions can lead to uneven ageing, including deposition of metallic lithium, and SEI growth at certain parts of the electrodes [70]. High-rate discharge means a short period of time for Li-ion transfer. In such conditions, ions are not fully de-intercalated, which results in capacity fade and lithium dendrite formation. Higher current rates also lead to higher internal temperature, encouraging side reactions that increase the loss of active material. There is always capacity fade and accelerated aging during high-rate discharge [50]. In an experimental study with post-mortem analyses, Mussa et al. show that the dominant degradation mechanisms may depend on C-rates [71]. For example, 3 C charging resulted in additional lithium plating, while 4 C charging resulting in graphite exfoliation and gas evolution [71]. Wang et al. note that different charging protocols perform best at different cycling temperatures, and that there is no one ideal charging protocol for all batteries [72].

Illustrating some of these degradation mechanisms, Fig. 3 shows that lithium ions are able to diffuse homogeneously throughout the electrode lattice at low current. With high charging current, the ion diffusion rate is slower than the charging rate, leading to an inhomogeneous distribution of ions throughout the lattice. This can cause lithium plating on the surface of the electrode, as well as stress-induced cracking and loss of active material.

A selection of recent experimental studies showing the extent to which each one of these variables degrades the battery is shown in Table 2. Significant differences can be seen in the severity of degradation depending on the battery chemistry, the specific test conditions, and the extent to which other degradation variables are simultaneously affecting the battery. Nevertheless, the cycling temperature, SoC, and charge rate, as well as the storage temperature each have a significant impact on battery degradation rate.

4. Battery manufacturer recommendations

In addition to the academic literature, publicly available information from a variety of companies was surveyed for instructions, guidance, warnings, or tips regarding the use and maintenance of LIBs in the company's products. These companies include 10 cellphone manufacturers, 10 laptop manufacturers (3 companies produce both phones and laptops), 4 power tool manufacturers, and 10 EV manufacturers. The majority of companies provide battery-specific information in an owner's manual/user guide, as well as on a product support website.

Table 2
Recent experimental literature regarding Li-ion battery degradation in response to key variables including temperature, state of charge, and charging rate.

Key Variable	Experiment Type	Cell Characteristics	Key Results	Study
Temperature	**Cycling**	40 Ah, pouch, NMC/graphite	At 23 °C, 2600 cycles to reach 80% capacity At 45 °C, 2000 cycles to reach 80% capacity At 45/65 °C (charge/discharge), 800 cycles to reach 80% capacity	Jalkanen et al. 2015 [73]
	(constant cycling at 1 C rate)	1.5 Ah, 18650, 1:1 NMC + LMO/graphite	At 25 °C, 65+ days to reach 80% capacity At 50, 60, 70 °C, it took 50, 35, 22 days respectively At 0, −10, −20 °C, it took 22, 10, 7 days respectively	Waldmann et al. 2018 [39]
	Storage (stored at 100% SOC)	2.85 Ah, 26650, LFP/graphite	At 10, 15 °C, 3.7% loss in 230 days, at 25 °C, 4.6 % in 230 days, at 35 °C, 5.0% in 150 days, at 45 °C, 5.9 % in 100 days, at 55 °C, 7.0% in 70 days	Schimpe et al. 2018 [74]
	(stored at 50% SOC)	2.15 Ah, 18650, NMC + LMO/graphite	After one year, stored at 25 °C had 99% initial capacity, stored at 45 °C had 93 % initial capacity, stored at 60 C had 70% initial capacity	Wu et al. 2017 [75]
State of Charge	**Cycling** (depth of cycling)	1.5 Ah, pouch, LCO/graphite	Cycling 0%-100%, 800 equivalent full cycles retained 82% of initial capacity Cycling 20%-80%, 800 equivalent full cycles retained 90% of initial capacity	Saxena et al. 2016 [76]
	(average SOC)		Cycling 40% to 100%, 750 equivalent full cycles retained 89% initial capacity Cycling 20% to 80%, 750 equivalent full cycles retained 91% initial capacity Cycling 0% to 60%, 750 equivalent full cycles retained 97% initial capacity	
	Storage (stored at 45 °C)	2.85 Ah, 26650, LFP/graphite	In 235 days, the battery stored at 0% lost 1.5% capacity; 25% lost 4.4% capacity; 50% lost 5.6 % capacity; 75% lost 6.2% capacity; 100% lost 8.0% capacity	Schimpe et al. 2018 [74]
	(stored at 25 °C)	1.06 Ah, 18650, LFP/graphite	Stored for 10 months. 30% SOC had 99% initial capacity, 60% SOC had 97% initial capacity, 100% SOC had 95% initial capacity	Zheng et al. 2015 [77]
	(stored at 40 °C)		Stored for 10 months. 30% SOC had 94% initial capacity, 60% SOC had 92% initial capacity, 100% SOC had 88% initial capacity	
	(stored at 55 °C)		Stored for 10 months. 30% SOC had 85% initial capacity, 60% SOC had 79% initial capacity, 100% SOC had 75% initial capacity	
Charging rate	**Cycling** (CCCV)	1.25 Ah, 18650, LMO + NMC/graphite 1.1 Ah, 18650, NMC + LCO/graphite 1.1 Ah, 18650, LFP/graphite	80% capacity was reached at 900 cycles (1A), 750 cycles (3 A), 550 cycles (5 A) 80% capacity was reached at 1050 cycles (1 A), 1000 cycles (3 A), 975 cycles (5 A) At 1200 cycles, 98% capacity remaining (1 A), at 1200 cycles 96% capacity remaining (3 A), at 750 cycles, 70% capacity remaining (5 A)	Keil & Jossen 2016 [78]
		2.4 Ah, 18650, LCO/graphite	At 0.5 C, reached 85% in 900 cycles; 0.8 C, reached 85% in 800 cycles; 1 C, reached 85% in 630 cycles; 1.2 C, reached 85% in 500 cycles; and 1.5 C, reached under 80% in 300 cycles.	Gao et al. 2017 [79]

4.1. Cellphones

Apple, Google, HTC, Huawei, LG, Motorola, Nokia, Samsung, Sony, and ZTE all provide product manuals that include information for safely operating and effectively managing batteries in their phones, and 7 of the 10 also have a customer support website offering additional battery information. Four common strategies relate to high temperature, low temperature, moisture, and mechanical damage. High temperatures are identified as a cause of degradation and potential safety issues across the board, although some [80–87] do not cite specific temperatures. When specific temperatures are cited, different temperatures are usually given for cycling and storage. For cycling, maximum temperatures of 35 °C [88–91] and 45 °C [92] are given, though for optimal performance temperature should not be above 25 °C [93]. When not in use, below 45 °C is the most common restriction [88–90]. For low temperatures, a minimum required temperature for charging is 0 °C [88–90],92] or 5 °C [91], though above 15 °C is recommended for optimal performance [93]. When in storage, above -20 °C is the most commonly recommended temperature [88–90]. Every company includes a warning about safety risks and battery damage due to water 81,83,84,87,89–94], and mechanical damage from bending, puncturing, crushing, shredding, or incinerating the battery. To help prevent these safety hazards, users are instructed to never attempt disassembling or dismantling their battery [84,89,91,93.

Other recommendations appearing in product manuals or customer support pages are less universal. For instance, Samsung and LG suggest that their phones should not be allowed to discharge fully, and should be recharged starting at 20% [80] or at 10%-15% [82]. Others mention a reduced battery life if high-drain features (gaming, simultaneously running many applications) are used frequently [83,85]]. Nokia and Sony mention potential damage if the device is left charging after reaching 100% charge [93,95]. Nokia instructs that charging should never last over 12 hours [93]. Sony offers a feature that detects the user's charging patterns, including typical unplugging time, and adjusts the charging rate so the battery will reach 100% shortly before then [95,96].

4.2. Laptop computers

Acer, Apple, Asus, Dell, HP, Lenovo, LG, Microsoft, Samsung, and Toshiba laptops each come with user guides, and the majority of these companies also have a support page with battery information. Every one of these companies provides information or warnings about high temperatures, low temperatures, water damage, and mechanical damage. While in use (including charging) the maximum temperature is 35 °C [88,97–107]. When not in use, maximum recommended temperatures include 40 °C [105], 45 °C [88,108], 60 °C [98,109], and 65 °C [103]. However an ideal temperature, both for storage and use, is no more than 25 °C [110] or 30 °C [108,111]. The lowest temperatures recommended for charging are 0 °C [103,104,106,108], 5 °C [98,100,101,107], and 10 °C [88,99,102,105]. When in storage temperatures can be as low as −5 °C [105], −20 °C [88,98,100,101], or −40 °C [103]. Ideally the computer would be operated above 15 °C [106]. And below certain temperatures, the computer's BMS may limit the charging current to preserve the battery [105]. In addition to acceptable temperature ranges, many companies give acceptable humidity ranges for their products, and every company warns users to never allow batteries to get wet [97–99], [102,103,105,106,109,112,113]. All ten companies include standard language about never puncturing, disassembling, or incinerating the battery [94,98,99,102,105–107,109,110,112,114], and some include more rare circumstances including “Never hit the battery with a hammer” [98] and “Keep the battery from being chewed by pets” [105].

Most laptop manufacturers also caution users against overdischarge of their batteries, reminding them to partially charge batteries before storing the laptop, and to recharge the batteries every several months while stored [88,97,99,106,110,113,115]. Others instruct users to avoid fully discharging the battery [116] and to begin recharging at 20% [113]. Companies also caution against leaving the laptop plugged in after it has completed charging [106]. In most laptops, the BMS will cease charging once the laptop has reached 100% SoC, and will not resume charging until the laptop has reached 95% SoC [97,99,105,110,115] to preserve battery health [97,99,115]. Still, it is recommended that users avoid leaving the battery at a high SoC for extended periods of time [88,105,111,117]. When using the laptop, HP notes that more intense uses, such as 3D graphics, will degrade the battery more quickly than other tasks [110]. The power saving modes that many companies offer, [88,97,98,100,102,104,105,113,117,118] though primarily intended to extend battery life (time between charging events), have the side effect of extending battery lifetime. Finally, many laptop manufacturers (as well as cellphone manufacturers) recommend that the battery should be allowed to fully discharge, to be followed by a full charge, at least once every month [82,97,102,104,110,111]. This is done to calibrate the BMS and not to preserve battery health.

4.3. Power tools

Bosch, DeWalt, Makita, and Milwaukee Tool provide guidance on batteries in their cordless tools. Bosch, Makita, and Milwaukee all provide owner's manuals for their products, while DeWalt offers a website on battery use. The only instructions offered by all four companies involve avoiding high and low temperatures. For charging, these companies recommend a maximum temperature of 40 °C [119] or 45 °C [120,121]. For storage, the recommended maximum temperature is 45 °C [121], 49 °C [120], or 50 °C [122]. Makita allows for a discharging temperature of up to 60 °C [121]. For charging, a minimum recommended temperature is 0 °C [120,121] or 4 °C [119]. Many chargers include protections that do not allow the battery to be charged until a minimum (or maximum) temperature is met [122,123]. For storage or discharging, temperatures as low as -20 °C may be appropriate [121].

While every power tool company included information about appropriate temperatures for their batteries, additional information was offered by some of the companies, including don't store the battery in the charger [120], don't run down the battery completely [119], and that in very high current draw scenarios (high torque, stalling) the battery pack may turn itself off [122]. Lastly, each company made safety recommendations, including to avoid charging in rain or snow [120,122,123], and to avoid damage by dropping, bending, crushing, puncturing, disassembling, or intentionally shorting the battery [120–122].

4.4. Electric vehicles

BMW, Chevrolet, Ford, Fiat, Honda, Hyundai, Kia, Mercedes-Benz, Nissan, and Tesla all include information about batteries in their owner's manuals. The most commonly identified sources of degradation are (in order): high temperature [124–133], low temperature [124–127,129–133], overdischarge [124,125,127–132], and fast charging [125,127,129,130]. Every manufacturer includes a warning about high temperatures, though different strategies are suggested, ranging from avoiding parking in the sun on hot days [131], to plugging in the car anytime it is hot, thereby allowing the battery cooling system to run as needed [124,126]. When the vehicle is running or charging, the BMS will regulate the temperature of the batteries, so it is most important to be aware of high battery temperatures when the vehicle is parked while not charging. Most companies do not cite a specific high temperature to avoid; those that do use either 50 °C [133] or 60 °C [124].

Low temperatures are also cited by almost all EV owner's manuals. As with high temperatures, plugging in the vehicle when it is cold is

recommended, so the battery heating system can run on grid power. Nissan explains that the battery warmer will automatically activate below a certain temperature, unless the battery is both not plugged in and under 15% charge (to avoid overdischarge) [127]. Additionally, when the vehicle is plugged in, the BMS will measure the temperature and take the appropriate warming or cooling action before charging begins [124–127,131], and may disable fast charging capabilities [130]. Mercedes-Benz emphasizes that extremely low temperatures for extended periods of time may cause irreversible damage necessitating battery replacement [132]. The lower temperature limit for batteries is cited as −25 °C [127,132] or −30 °C [124,131]].

Overdischarge will typically not occur during operation. The BMS will turn off the car and cease operation before serious degradation will occur. However, if the 'empty' battery is then left for an extended period of time without being recharged, the battery can enter an overdischarge state due to the slow self-discharge that occurs even when the battery is not operating. Some manufacturers are very specific, instructing owners not to leave the vehicle parked for more than 2 weeks with a low battery [124,132]. Others are more general, simply advising that the battery not be run all the way down, or left idle for extended periods of time [128–131].

The majority of manufacturers do not include information in their manuals explaining that fast charging can lead to accelerated battery degradation. Those that do, say that use of fast chargers should be minimized to maximize battery lifetime [125,127,130,131. Specific recommendations made by companies of each device type are highlighted in Table 3.

4.5. Comparing manufacturer instructions and academic literature

The different audiences for academic literature and manufacturer instructions necessitate differences in how information is presented. While academic studies often give very specific insights about battery performance in response to one or occasionally two key variables, manufacturer instructions give broad and actionable information to users. Despite the differences in granularity and specificity of the information presented, the underlying information given should be the same. However, we have found that this is not true in all cases. In Fig. 4, variables affecting battery degradation, identified from both academic literature and manufacturer guidance, are compared with the percentage of companies making a recommendation related to that variable.

Fig. 4a shows the comparison in total, while Fig. 4b–e shows industry recommendations for each device type. Electric vehicles (Fig. 4e) exemplify some of the insights that can be drawn from such data. No EV companies recommend against keeping the battery at 100% state of charge. This is because keeping the vehicle plugged in allows the BMS to control battery temperature using power from the grid, which is deemed more important, as well as potentially more palatable, than telling users to leave their vehicle less than fully charged. In contrast, only 40% of EV companies include warnings that fast charging can cause faster battery degradation, and in this case there is no lifetime benefit (like controlling temperature from grid power) for excluding this information. This information may be excluded because the EV manufacturers are very confident that their fast charging protocols can minimize degradation, that they don't believe users will use fast chargers often enough to necessitate such a warning, or that including such information would hurt the sales or marketing of the vehicle.

Recommendations may also not be included depending on the device's expected replacement time. Cellphones (Fig. 4b) include fewer warnings against high and low state of charge than laptops (Fig. 4c). This may be because users often replace cellphones before the degradation becomes significant (replacement cycle length of 2.8 years in the US), while users expect longer lifetimes from their laptops (replacement cycle length of 6.9 years in the US) [135].

Lastly, some recommendations are not included because the variables are outside of the user's control, and therefore the company has no reason to provide behavioral advice in that area. For example, a laptop (Fig. 4c) or a power tool (Fig. 4d) with a single charging protocol predetermined by the manufacturer would not need to provide a warning about degradation from fast charging.

Table 3
Examples of advice, instructions, or warnings offered in industry sources regarding Li-ion battery storage and operation, sorted by key degradation variable.

Key Variable	Device Type	Recommendation	Company
Temperature	Cellphone	0 °C to 35 °C when cycling, −20 °C to 45 °C when in storage	Apple [88]
		Use between 15 °C and 25 °C for optimal performance	Nokia [93]
	Laptop	Charge between 10 °C and 35 °C	Lenovo [99]
		Operating 0 °C to 35 °C, storage −40 °C to 65 °C	Dell [103]
	Power Tool	Charge between 0 °C and 45 °C	Bosch [120]
		Store 20 °C to 45 °C, charge 0 °C to 45 °C, discharge −20 °C to 60 °C	Makita [121]
	EV	Keep between −30 °C and 60 °C, plug in when warm or cold	Tesla [124]
		Plug in when below 0 °C	Chevrolet [126]
		On hot sunny days, avoid parking under direct sunlight	Honda [131]
State of Charge	Cellphone	It's best not to let your battery go under 20%	Samsung [80]
		Continuous charging should not exceed 12 h	Nokia [93]
	Laptop	Avoid having your surface plugged in 24/7	Microsoft [134]
		Lifespan is adversely affected by constantly charging the battery/device when already at full capacity	Acer [106]
	Power Tool	Completely running down a battery may damage it	DeWalt [119]
		Don't store the battery in the charger	Bosch [120]
	EV	Do not leave the vehicle parked for longer than 14 days with a high voltage battery below 20% state of charge	Mercedes-Benz [132]
		If allowed to discharge too much, the battery may become damaged	Honda [131]
Current	Cellphone	Battery lifespan may decrease if you keep many apps and functions running simultaneously and continuously	LG [83]
	Laptop	More intense uses (ex. 3D gaming) will degrade battery more quickly	HP [110]
	EV	Repeated use of this charging method [DC Charging] could have a long term effect on the battery	Ford [125]
		Use of fast charge should be minimized in order to help prolong high voltage battery life	Hyundai [129]
		Minimize use of public Fast Charge or Quick Charger	Nissan [127]
Other	Cellphone	Don't expose your phone to liquids	Google [89]
		Do not disassemble, open, crush, bend, deform, puncture, shred, or submerge the battery	Motorola [92]
	Laptop	Avoid storing batteries in damp environments	Asus [113]
		Do not crush, drop, mutilate, or penetrate the battery	Dell [115]
		Batteries should be calibrated once every two to three months	HP [110]
	Power Tool	Do not charge battery pack in rain, snow, damp or wet conditions	Milwaukee Tool [122]
	EV	Battery should not be serviced by the owner	BMW [128]
		Never inspect, remove, or disassemble an of the high voltage components in your vehicle	Kia [130]

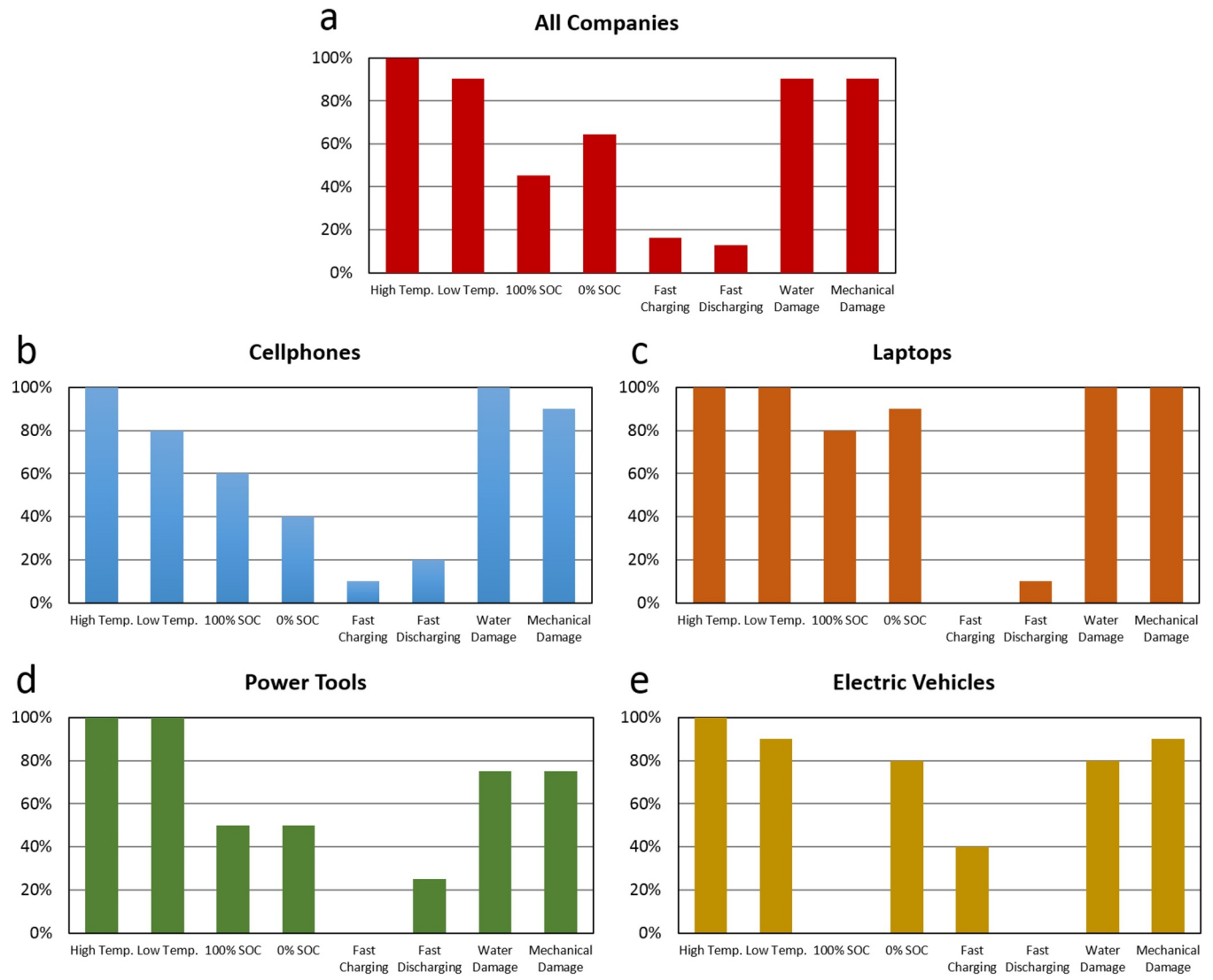

Fig. 4. Percentage of surveyed companies warning users against exposure to certain conditions for a) all companies surveyed, and b–e) by manufacturer of each device type surveyed.

5. Battery lifetime improvement

Maximizing battery lifetime has environmental and economic benefits; but to maximize lifetime, one must avoid storage and use conditions that accelerate degradation. Avoiding these adverse conditions is the responsibility of a device's BMS and user actions.

5.1. Benefits of battery lifetime improvement

The environmental benefit of LIB lifetime extension is due to reduced demand for and production of new and replacement batteries. For example, manufacturing a single Dell laptop battery (<1 kg) results in 10 kg of CO_2e emissions [136] . In general, manufacturing has a dominant share in CO_2e emissions of average cellphones, tablets, and laptops [137]. A report by Green Alliance claims that extending the lifetime of a cellphone by 1 year reduces by 1/3 the lifetime CO_2e impact of the device [137]. Along with energy use and resulting emissions, battery production also contributes to ozone depletion, photo oxidation formation, particulate matter formation, terrestrial, freshwater, and marine eutrophication, freshwater and marine toxicity, terrestrial acidification, and the human health impacts of each of these [138].

In addition to environmental benefits, there are clear economic incentives for users to extend battery lifetime. For Apple devices, battery replacement cost (out of warranty) is a substantial percentage of total device cost, at 5%–9% for phones [139], 12%–30% for tablets [140], and 7%-15% for laptops [141]. For power tools this can be even more extreme. Depending on the battery and tool, a battery could cost twice as much as the tool itself [142–144]. And a BEV battery pack represents 35%-50% of the total price of the vehicle [145]. Though EV battery costs have fallen dramatically in recent years, the U.S. Department of Energy goal of $125/kWh production cost by 2020, if met, results in a production cost of $7,500 for a 60 kWh battery to $12,500 for a 100 kWh battery, which remains a substantial percentage of vehicle cost [146].

5.2. The role of battery management systems and state of health monitoring

Failure of LIBs can cause hazardous problems including fire and explosions, in addition to inducing additional costs for repair or replacement [15,147]. The status and health of LIBs need to be checked and controlled regularly in order to detect faults, correct them, and predict remaining useful life, while addressing safety issues [15]. To ensure battery safety, the BMS includes battery fault diagnosis functions and gives early warnings and reports about unhealthy conditions as well as battery aging information [147].

To improve the performance of battery systems, the BMS protects against deep charge/discharge and accurately estimates the functional status of the battery including SoC, state-of-health (SoH), state-of-function (SoF), and state-of-safety (SoS) based on measurable outputs like temperature, voltage, and current 26,148]. For example, in EVs, it becomes critical to protect the battery during deep charges/discharges when traveling a long distance involves discharge of up to 80% or more [148]. Thermal management is also critical in an EV battery pack as it includes thousands of series and parallel cells, and therefore keeping temperature within the range of 30–40 °C will lead to increased battery efficiency [148]. The models used by BMS include adaptive algorithms and data driven estimation methods, which are compared with direct and indirect experimental analyses [149]. Use of large data sets and machine learning is being explored as a tool to improve these models [150,151]. It is also important to minimize the computational burden of models, so that they can be used on-board vehicles in real time [152]. Lastly, models are only as good as the experimental data on which they are based, so minimizing errors through implementing experimental control methods is critical [153].

The tasks performed by the BMS (at cell, module, and pack levels) include: preventing damage to cells and battery packs, ensuring proper operational voltage and temperature ranges, balancing SoC differences between cells, guaranteeing safe operation, extending battery service life as long as possible, and maintaining batteries in a healthy condition that will fulfill the vehicle requirements [147,148]. BMS inputs include current, voltage, and temperature sensors, vehicle control (in case of EVs) and digital inputs [147]. Outputs consist of thermal management modules including fans and electric heaters, and balancing modules including capacitors and switch arrays to equalize batteries, and manage voltage [147]. There are also digital outputs such as charging indicators and failure alarms [147].

5.3. User behaviors

Based on the academic literature and information provided in owner's manuals, user guides, and customer support websites, a list of behaviors was developed to illustrate nine best practices for maximizing Li-ion battery lifetime, shown in Table 4 and explained in more detail below. These best practices are general in nature, and written for the end users of products with LIBs. Every practice will not apply to every battery, as operating requirements and the role of the BMS vary between devices.

5.3.1. Temperature recommendations

Elevated temperatures can accelerate degradation in almost every component of LIBs. This impact is greatest when combined with high voltages, but can occur regardless of the SoC [27]. Furthermore, elevated temperatures can lead to significant safety risks, as gas may form within the battery increasing pressure to the point of explosion. Recommended high temperature limits are stricter when in use than when in storage. Typically, if a device is noticeably hot when charging, it should be unplugged. However, most EV manufacturers recommend that vehicles should be plugged in when the ambient temperature is hot, so the vehicle's battery cooling system can operate directly from grid electricity.

When a battery is cycled at low temperatures it is more susceptible to lithium plating, which can lead to internal short circuits irreparably damaging the battery, and potentially causing safety issues. For power tools and EVs, chargers will not begin charging until the device has reached an appropriate temperature, and for EVs this may include the use of a battery heating system. If a heating system is in place, most EV manufacturers recommend leaving the vehicle plugged in when it is cold.

5.3.2. State of charge recommendations

There are two main strategies to minimize time spent at 100% SoC. First, devices can be partially charged, unless a full charge is needed. For example, if 30% of a battery's capacity is needed on a given day, cycling from 80%-50% places less stress on the battery than 100%–70% [76,154]. Second, devices should be unplugged once they reach 100% SoC.

Just as high SoC places stress on a battery, so too does low SoC. A device's BMS will shut down a device before it reaches true 0%, to avoid overdischarge, which can permanently damage the battery. Despite this precaution, a device will still reach overdischarge if it is not charged for a long period of time.

Battery users do not have a good understanding of the impact of extreme states of charge on their battery. Results from a 2017 survey, displayed in Fig. 5, show roughly equal numbers of people agreeing and disagreeing with statements that ask whether high or low states of charge can damage a battery [155]. Furthermore, this study showed that the most common charging behavior for cellphones was charging on a fixed routine (for example overnight) and for laptops was leaving the device plugged in whenever possible [155]. Androulidakis et al. found that 45% of cellphone users charge their phones overnight, and only 10% do partial battery charges [156]. Ferreira et al. has found that even as more charging opportunities become available over time, users still prefer a fixed charging schedule, frequently overnight [157].

5.3.3. Current recommendations

Fast charging is convenient, but it comes with a trade-off. Repeated use of fast chargers will degrade a battery more quickly than standard charging. Discharging a battery too quickly leads to battery degradation through many of the same mechanisms as fast charging. One way to determine if a battery is discharging too quickly is if it is noticeably hot. Discharging currents can be controlled by the user to various degrees depending on the device. For cellphones and laptops, lowering screen brightness, turning off location services, and quitting high power using applications can help. For power tools, choosing a tool with sufficient power output for the task at hand is important. And for EVs, driving habits, such as limiting sudden starts and stops, will impact the battery pack's discharging current.

5.3.4. Additional recommendations

Even in battery packs designed to be waterproof, exposure to water can lead to serious faults if the integrity of the pack or cells have been compromised, through mechanical damage or otherwise. Once inside the pack, water can externally short circuit cells; if cells are

Table 4
Best practices for maximizing the lifetime of Lithium-ion batteries.

1.	Minimize exposure to high temperatures, in storage and use	Temperature recommendations
2.	Minimize exposure to low temperature, especially when charging	
3.	Minimize time spent at 100% state of charge	State of charge recommendations
4.	Minimize time spent at 0% state of charge	
5.	Avoid using fast charging	Current recommendations
6.	Avoid discharging device more quickly than is needed	
7.	Avoid use or storage in high moisture environments	Additional Recommendations
8.	Avoid mechanical damage	
9.	Follow manufacturer's calibration instructions	

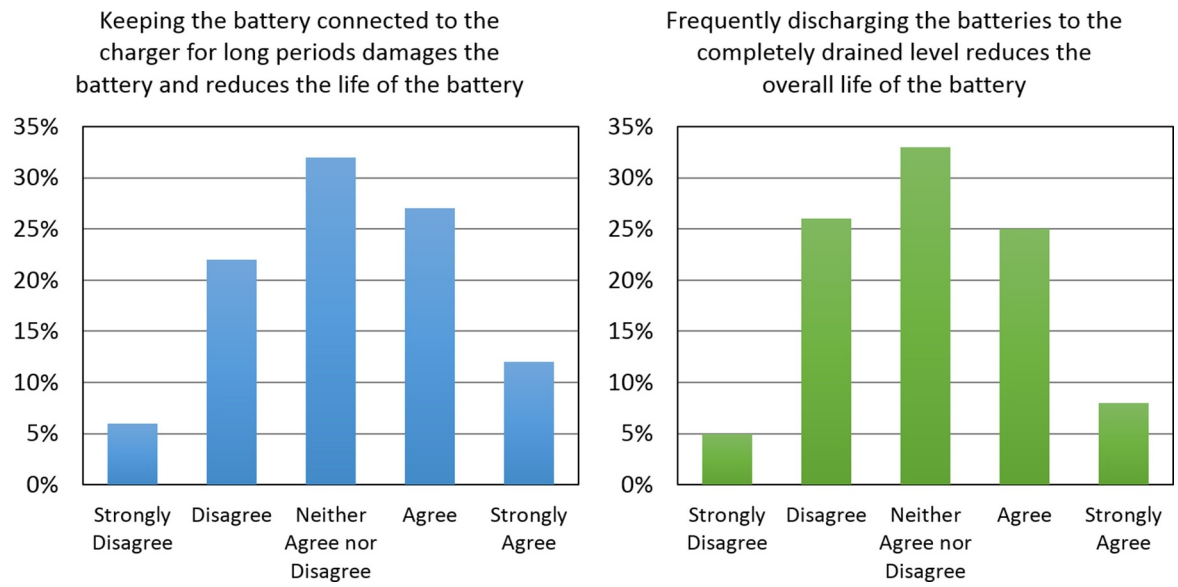

Fig. 5. Results from a survey conducted by Saxena (2017) [155] illustrating that users do not have a good understanding of behaviors that can decrease battery lifetime.

compromised, electrolyte may escape the cells and external moisture and/or humidity may penetrate the cells. The former leads to combustible gases, the later to side reactions and other possible failure modes [e.g., 158].

Mechanical damage to a battery covers a wide range of things. This includes puncturing the battery, severely bending the battery, or directly connecting the leads of the battery. Mechanical damage to the battery's interior structure can also occur if the battery is dropped or crushed. Anything that short circuits the battery will render it inoperable, and result in safety risks. Finally, due to the risk of explosion, batteries should never be incinerated.

Often manufacturers will recommend that devices (particularly phones and laptops) be fully discharged and then fully charged at least once a month. Though this contradicts other recommendations, this process is important to calibrate the battery management system. A full discharge-charge cycle allows the device to measure its own capacity, so that it displays the remaining battery life accurately. Note that this calibration does not actually have a significant impact on battery lifetime, and is different than battery conditioning, which is often required for chemistries other than Li-ion. It simply improves the accuracy of battery state estimations. Improving the accuracy of SoH estimations is an active research area, with new methods continually being developed [159].

6. Conclusion

Lithium-ion batteries inevitably degrade with time and use. Almost every component of the battery is affected, including the anode, cathode, electrolyte, separator, and current collectors. A wide variety of mechanisms contribute to degradation, and these mechanisms are sensitive to storage conditions and use patterns, including temperature, SoC, and charging/discharging rate.

By minimizing exposure to the conditions that accelerate degradation, batteries can last longer. This has a positive environmental impact, as battery production is a source of GHG emissions and many other pollutants. Additionally, there are significant financial incentives for users to avoid adverse conditions, as the cost of batteries can range from 5% to over 50% of a product's total cost. Despite these clear benefits, user understanding of proper battery management is lacking and guidance provided through product manuals and company websites often is scattered, contradictory, or non-existent.

Additionally, there is a significant lack of knowledge regarding how users operate batteries. Limited research has shown user knowledge of battery health issues to be poor, but further survey data are needed to establish actual battery use patterns to quantify the net impact of user behavior on battery lifetime. Identifying areas in which user knowledge and behavior differ will be important for designing battery management systems and practices that preserve lifetime.

We present a review of mechanisms that lead to degradation of active and inactive materials and shortened lifetime of Li-ion batteries. We also investigate the recommendations provided by industry regarding preserving battery health in cellphones, laptops, power tools, and EVs. Then, based on the academic literature and publicly available information, a list of nine best practices for extending Li-ion battery lifetime is developed. The first six practices are related to three main variables that impact battery health: temperature, state of charge, and current. The rest are more general guidelines to reduce damage to the device. Improving user awareness of these best practices is an important step towards responsible battery management.

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CRediT authorship contribution statement

Maxwell Woody: Investigation, Data curation, Writing - original draft. **Maryam Arbabzadeh:** Investigation, Data curation, Writing - original draft. **Geoffrey M. Lewis:** Investigation, Writing - review & editing. **Gregory A. Keoleian:** Conceptualization, Methodology, Investigation, Supervision, Writing - review & editing. **Anna Stefanopoulou:** Writing - review & editing.

Declarations of Competing Interest

None.

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Supplementary materials

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