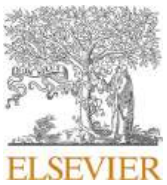
Journal of Energy Storage 144 (2026) 119694



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Journal of Energy Storage

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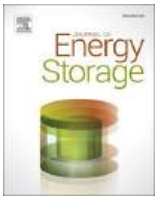

Review article

A comprehensive overview of lithium-ion batteries for electric vehicles: Materials, performance, safety, recycling, and emerging technologies

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ARTICLE INFO

Keywords:
Lithium-ion batteries
Electric vehicles
Safety
Recycling
Thermal runaway

ABSTRACT

Electrifying the transportation sector is one of the most important ways to combat climate change and reduce greenhouse gas emissions related to dependence on fossil fuels. Lithium-ion batteries (LIBs) are considered one of the most promising candidates for powering next generation electric vehicles (EVs) due to their high energy density, extended cycle life, and compact size. Despite the continuous development, EVs powered by LIBs still have several limitations compared to conventional internal combustion engine vehicles (ICEVs). These include limited driving range, slow charging times, high safety concerns and reliance on scarce and toxic raw materials. These several challenges are almost related to the specific battery chemistry and cell design, and influence, not only the battery performance and cost but also its safety. In this context, this manuscript provides a comprehensive overview of LIB technology for EV applications, with a detailed analysis of recent advancements and key challenges across the main research areas. In particular, by presenting an integrated discussion that covers LIB materials, performance, degradation mechanisms, safety issues, recycling strategies and emerging technologies, the paper aims to support the development of batteries that can meet the stringent demands of future EV applications.

1. Introduction

The transportation sector plays an important role in modern life, allowing people, businesses, and families across the globe to stay connected and boosting economic growth at the same time. However, it is also one of the biggest causes of climate change, especially because its overdependence on fossil fuel releases a lot of carbon dioxide (CO_2) into the atmosphere every day. At present, transport vehicles powered by petrol and diesel contribute almost one-fifth of global energy-related greenhouse gas (GHG) emissions, a number growing with speed [1], [2].

To overcome this problem, important efforts are being made toward decarbonization and transitioning to sustainable energy solutions [3]. Many governments including those of France, Germany, the United Kingdom and the Netherlands announced plans to ban the production of petrol vehicles by 2025 to 2040 [4].

With their technological and environmental benefits, electric vehicles (EVs) have become an attractive alternative in the automotive sector [5]. EVs, which are powered by rechargeable batteries, are classified as fuel cell electric vehicles (FCEVs), plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs), and full battery electric vehicles (BEVs) [6]. Table 1 lists the specific characteristics and operating principles of each of these technologies [7], [8].

Compared to conventional internal combustion engine vehicles (ICEVs), EVs provide a cleaner and more sustainable mobility solutions [9], [10]. As an example of the substantial environmental advantages of electrification, Fig. 1 shows the main differences between ICEVs and EVs with regard to energy sources, powertrains, and emissions.

EVs have a nearly two-century history, despite being frequently seen as a modern invention. Jedlik Anyos proposed the concept in 1828 [11], but a practical EV was not introduced until 1859, after French physicist Gaston Planté developed the first rechargeable battery [12]. With over 33,000 vehicles registered in the United States, BEVs dominated the automotive market by the early 1900s [11]. However, when ICEVs were introduced around 1910, interest in electric mobility began to wane. This shift was largely due to the high costs of EVs, their limited range of

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https://doi.org/10.1016/j.est.2025.119694
Received 30 April 2025; Received in revised form 25 September 2025; Accepted 30 November 2025
Available online 8 December 2025

Table 1
Operating principle and key features of EV technologies [7], [8].

EV Type	Operating Principle	Key Features
BEV	Relies entirely on electric motors powered by batteries, with no ICE	➢ Zero emissions ➢ Independence on crude oils ➢ Rechargeable via electric external sources ➢ Good driving range
HEV	Uses both ICE and an electric powertrain. Operates on electric propulsion at low power demands and switches to ICE for higher power needs	➢ Low emissions ➢ Dependence on crude oils ➢ Long driving range
PHEV	Similar to HEVs but with higher-capacity batteries that can be externally charged, allowing for extended fully electric operation.	➢ Very low emissions ➢ Dependence on crude oils ➢ Rechargeable via electric external sources ➢ ICE as backup for extended range
FCEV	Generates electricity using a fuel cell from hydrogen (stored in high-pressure tanks) and oxygen from the air to drive an electric motor. A battery is needed for storing additional energy and managing power peaks.	➢ Zero emissions (water byproduct) ➢ Independence on crude oils ➢ Hydrogen refuelling ➢ Satisfied driving range

just 40 miles, and their top speed of only 45 miles per hour [13].

The energy crisis and oil embargo of the 1970s renewed attraction in EVs, highlighting the need for ICEV substitutes. [14]. Improvements in battery technology were evident during this period, with lead-acid (Pb-acid) batteries powering the first generation models (range ≈ 80-100 miles) [15], [16] and nickel-based batteries (nickel-cadmium (Ni-Cd) and nickel-metal hydride (Ni-MH)) extending the ranges of the second-generation EVs to 100-140 miles [17]. Nevertheless, EVs still had many challenges in competing against the driving dominance and performance of ICEVs.

Since the early 1900s, the main obstacle to the widespread adoption of EVs has been the development of low-cost, high-performance battery systems [18], [19]. Lithium-ion batteries (LIBs or Li-ions) are currently the most popular electrochemical energy storage solution [20], which dominates the market for portable electronics [21], and shows at the same time great potential as a technology for next-generation EVs [22], [23]. In contrast to previous EV battery technologies such as Pb-acid, Ni-Cd, and Ni-MH, LIBs show higher energy densities, a longer lifespan, lower self-discharge rates, and a more compact, lightweight design [24], [25], [26]. These important advantages are driving the rapid expansion of the global battery market, which is expected to exceed 2500 GWh within five years, as illustrated in Fig. 2(a) [27]. In addition to this, Fig. 2 (b) shows that, across the main applications, electric mobility is the primary market driver for the growing demand for batteries [28].

The 2016 Paris Agreement, aimed at reducing global GHG emissions [29], [30], [31], has rapidly accelerated the development of EVs powered by LIBs by driving improvements in battery affordability and performance. Automakers like Mercedes-Benz, BMW, and Volkswagen are spending billions in EV production, with Volkswagen wanting to obtain the market leadership by 2025 [32]. At the same time, governments in the United States, EU, and China are making heavy investments in EV research, funding, and infrastructure [33], [34], [35]. Thanks to these combined efforts, EVs powered by LIBs have grown at the fastest rate in the world. This expansion is illustrated in Fig. 3, which shows the increase in EVs over the past seven years [36], [37]. Notably, EV sales increased from less than 5 million in 2017 to around 60 million worldwide by 2024, despite the COVID-19 pandemic. A major driver of this expansion was China, which significantly contributed to the increase in EV global sales [38].

Despite the great advantages provided by LIBs, EVs still face several challenges when compared to conventional ICEVs. These include limited driving range [39], [40], slow charging rates [41], reduced battery lifetime [42], high costs [43], [44], [45], safety [46], reliability [47], and insufficient charging infrastructure [48], [49], [50], all of which continue to hinder their widespread adoption.

To overcome these limitations and be comparable to ICEVs, the European Council for Automotive R&D (EUCAR) focuses on increasing the energy density (> 450 Wh/kg) and power density (> 1000 W/kg) of LIB cells and reducing at the same time costs to less than €70 per kWh by 2030 [51]. This will allow future EVs to reach a driving range greater than 600 km between charges [51]. In addition to range and cost, other important factors need to be considered, such as increasing battery calendar life to at least 10 years, improving charging infrastructure to support charging times of 15 minutes or less, ensuring high safety standards and implementing advanced recycling strategies [52], [53], [54].

In pursuing these advancements, it becomes essential to consider the interconnected nature between LIB chemistry, performance, safety, and recyclability, especially when evaluating their possible use in next-generation EVs. The chemistry of a LIB not only dictates performance and cost but also greatly affects safety [55], [56]. For instance, certain LIB chemistries offer higher energy density but present greater safety concerns [57], [58]. Voltage, current and temperature are key drivers of battery electrochemical reactions and degradation processes that can lead to LIB failure [59]. Thus, a deep understanding of the materials that constitute LIBs is essential to assess their safety.

At the same time, also recyclability is strongly influenced by LIB chemistry [54]. Some high-performance LIB chemistries depend on scarce or toxic materials, which makes efficient recycling processes essential at their end of life (EoL) [60], [61]. Moreover, some LIB chemistries used in EV applications have a relatively short lifetime that,

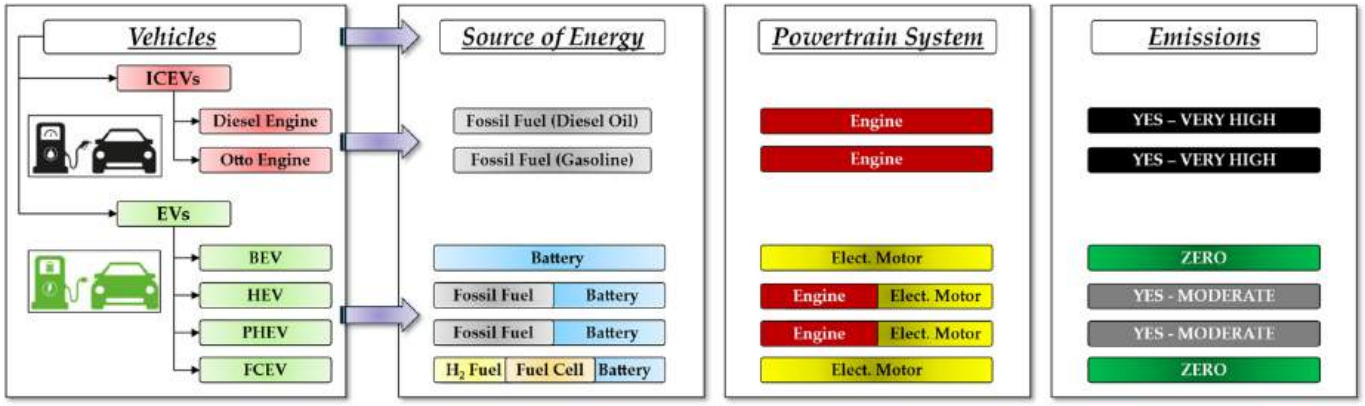

Fig. 1. Comparison of energy sources, powertrain systems, and emissions in ICEVs and EVs.

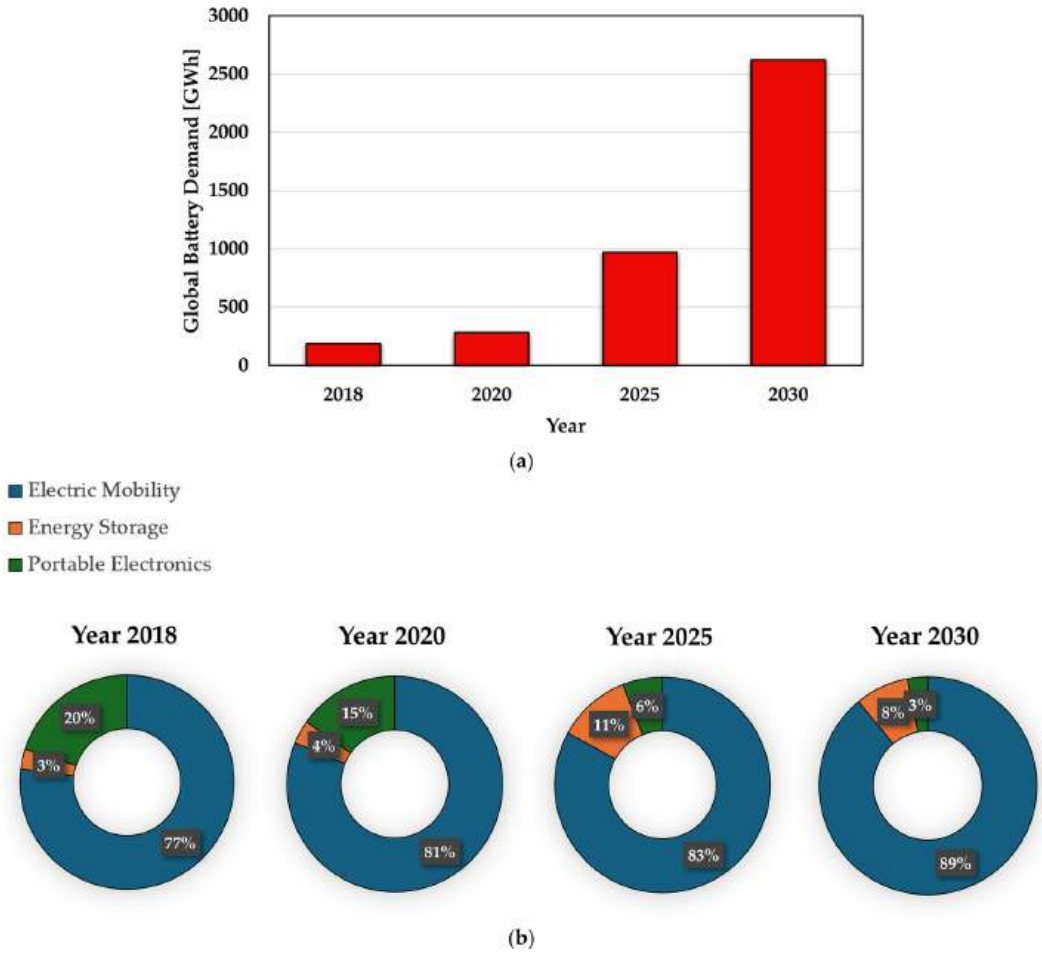

Fig. 2. Global battery industry: (**a**) Growth trends; (**b**) Demand across key applications.

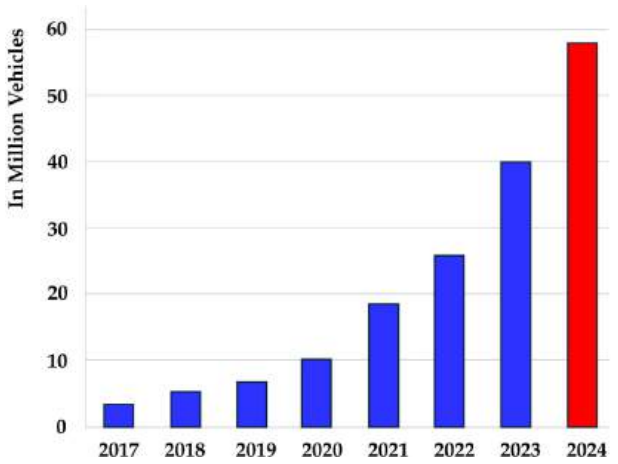

Fig. 3. Global stock of EVs, according to the International Energy Agency (IEA) [37].

if not addressed through improved materials, increases the urgency of developing sustainable EoL solutions. In this way, LIB performance, safety and recyclability are not separate considerations but closely linked to its specific chemistry.

In this context, the aim of this work is to provide a comprehensive overview of all critical areas of LIB technology related to EV applications. Unlike most previous studies, which focus on isolated aspects such as materials, performance, safety, or recycling, this review covers all the LIB key research domains (from electrochemistry and performance to safety, recycling and post technologies) in a single and detailed work. By bringing these diverse perspectives together, the review provides the scientific community with a unified and more complete resource to guide the future development of battery technologies for EVs.

The review begins by explaining the electrochemical fundamentals of batteries, describing in detail their key performance parameters and illustrating the targets of next-generation EVs (Section 2). A complete overview of LIB technology is then provided, including the operating principle, LIB classification, performance characterization, and degradation mechanisms (Section 3). Following this, a detailed analysis of commercial and research electrode materials for LIBs in EV applications is presented (Section 4). The main safety concern for LIBs, thermal runaway, is then discussed (Section 5). Strategies for battery recycling and end-of-life (EoL) management in the EV context are then evaluated (Section 6), followed by an examination of future battery technologies specifically aimed at advancing EV performance, energy density, and safety (Section 7). Finally, Section 8 presents an overall discussion and outlines future directions for battery technologies in EV applications.

2. Battery technology

Of all the EVs, as presented earlier in Fig. 1, BEVs are the most popular and commercialized [37]. Batteries, which can be considered as the heart of each EV, are essentially electrochemical energy storage systems that store and release energy.

The concept of the battery dates back to Alessandro Volta's discovery in 1800 [62]. In general, a battery consists of one or more electrochemical cells connected in series, parallel, or a combination of both,

based on the requirements for output voltage and energy capacity. As an electrochemical storage system, it enables the use of stored energy whenever and wherever needed. This energy is released through galvanic reactions, which occur when two materials (or electrodes) with different standard reduction potentials are connected through an external circuit to a load that in turn generates voltage [63]. In this case, the material with lower potential (i.e., the negative electrode) is oxidized and releases electrons into the external circuit, while the material with higher potential (i.e., the positive electrode) is reduced. Together, these reactions convert chemical energy into electrical energy via electron transfer.

There are two broad categories of batteries: primary (non-rechargeable) and secondary (rechargeable) batteries. Primary batteries irreversibly convert chemical energy into electrical energy, while secondary batteries can be recharged and reused by means of reversible electrochemical reactions. Nowadays, secondary batteries occupy a larger portion of the battery market and account for 73.8% of the overall market share [64]. LIBs are a type of rechargeable battery and are projected to account for over 80% of the secondary battery market due to their superior performance to the other battery technologies [65].

2.1. Key performance parameters

The main performance indicators of batteries are described by the following key parameters:

1. Open Circuit Voltage (OCV): represents the voltage when no current is flowing in or out of a cell or battery, and thus, no reactions are occurring inside [66]. It depends on the value of the battery state of charge and operating temperature [67]. However, it is important to note that OCV remains constant throughout the battery's lifetime [6].
2. Operating Voltage: is the voltage between the cell or battery terminals when a load is applied [6]. It varies with the value of the battery state of charge and charge/discharge current [66].
3. Nominal Voltage: indicates the reference voltage of a cell or battery. Specifically, it is the average value of the operating voltage, calculated between the maximum charge voltage (MCV), which is the voltage when the battery is fully charged, and the end-of-discharge voltage (EODV), which defines the battery's empty state [6].
4. Nominal Capacity: represents the maximum electrical charge which a cell or battery can store at a given C-rate [6]. It directly impacts the autonomy of EVs. The capacity measurement takes two different forms which depend on the electrode active material size: volumetric capacity (mAh/L) and specific capacity (mAh/g) [68]. The distinction between theoretical and practical capacity needs to be recognized. The theoretical capacity represents the highest possible charge that would store under ideal conditions by using all available electrode active material [69]. Real operating conditions determine the actual charge storage capacity which typically amounts to only 25–50% of theoretical values because of inefficiencies, side reactions and electrode active material structural changes [70].
5. C-rate: is the rate at which a cell or battery is charged or discharged [71]. It is generally written as C/r, where, r, is the time in hours taken to fully charge or discharge its nominal capacity, C. For example, considering a cell with a nominal capacity of 4 Ah, a C-rate equals to C/2 (2 A) means that the charge or discharge process will be completed in about two hours. It is important to note that the higher the C-rate, the lower the time required for battery charging or discharging.
6. Operating Temperature: refers to the range of temperatures in which a cell or battery can operate within the local environment. It has a direct impact on safety [72].
7. Self-discharge: indicates the reversible loss in capacity of a cell over time without any external electrical load, expressed as a percentage of its nominal capacity [73].
8. Efficiency: measures the capability of a cell or battery to convert electrical energy into chemical energy and vice versa. Usually, this evaluation is done using three parameters, namely the coulombic efficiency (CE), the voltage efficiency (VE), and the energy efficiency (EE) [74]. CE is defined as the ratio between discharge and charge capacity in a single cycle; VE accounts for the voltage difference between charging and discharging as a result of cell polarization; whereas EE, which is the product of CE and VE (i.e., EE = CE x VE), indicates how well the battery converts the energy provided during charging into usable energy during discharge.
9. State of Charge (SoC): gives measure a of the available amount of stored energy in a cell or battery and is expressed as percentage of battery capacity [6].
10. Deep of Discharge (DoD): states the energy used by cell or battery. Like SoC, it is provided as percentage of battery capacity. By definition, DoD = 1 - SoC [6].
11. Energy Density: represents the energy content of a cell or battery. Specific energy density (Wh/kg) and volumetric energy density (Wh/L) are obtained by multiplying specific and volumetric capacity with cell nominal voltage [75]. Thus, a cell with high energy density is then a cell that combines electrode materials which have high specific and volumetric capacity, and large potential difference.
12. Power Density: refers to the amount of power a cell or battery can deliver per unit of mass (i.e., specific power density (W/kg)) or volume (i.e., volumetric power density (W/L)) [75]. It thus determines how quickly energy can be supplied. Power density, as much as energy density, are both very important performance indicators for EVs. Power density determines their acceleration [76], while energy density, their driving distance [77].
13. Lifetime: the time between cell or battery's beginning of life (BoL), i.e., when its characteristics match those listed in the datasheet, and its end of life (EoL), namely, when its characteristics deteriorate and fall below a defined threshold [75]. In EVs, EoL is typically reached when storage capacity falls below 80% of the nominal capacity [78], [79]. Cycle life, or the number of charge-discharge cycles, and calendar life, or the amount of time a battery lasts when not in use, are two metrics used to measure battery lifetime [80]. Cycle life depends on full and partial cycles. Operating the battery in partial cycles can extend its lifespan [81]. Calendar life, on the other hand, is affected by factors such as operating temperature, charging conditions, and cell composition all of which can accelerate ageing and, thus, performance degradation [82].
14. Internal Resistance: is the quotient of change of voltage of a cell by the corresponding change in discharge current under specified conditions [83]. For LIBs, which typically range from 10 to 50 mΩ [84], it can be represented by ohmic resistance (i.e., the inherent resistance of cell components) and polarization resistance (i.e., resistance to the movement of lithium ions). This value, which is affected by operating temperature, C-rate, cell design, and degradation mechanisms, impacts performance in terms of battery energy and power output, efficiency, and lifetime [85].
15. State of Health (SoH): measures the cell or battery capacity degradation due to aging. It is defined as the ratio of the current available capacity to the nominal capacity [86]. Thereby, fast and accurate assessment of SoH becomes vital for battery safe operations [87]. Direct measurements can be carried out using the electrochemical impedance spectroscopy (EIS) method [88].
16. Safety: relates to the risk level of a cell or battery. Events such as fires and explosions limit practical applications, result in

economic losses, and damage battery technology's reputation. Commonly, the EUCAR hazard levels are adopted as a reference to classify the severity of safety risks during battery operation or failure. For example, a hazard level of 7 (maximum risk) corresponds to a battery explosion. For a detailed description of all risk levels, please refer to [51].

17. Cost: influences the widespread adoption of large-scale applications, such as EVs, which production has always been affected by the high cost of battery manufacturing [89].

Fig. 4 illustrates with two Ragone plots the energy and power performance range of commercial and emerging battery technologies for EV applications. Specifically, Fig. 4a compares specific energy density and volumetric energy density, while Fig. 4b contrasts specific energy density and specific power density, highlighting that energy output decreases at high discharge rates. Both graphs refer to cell-level performance and indicate the target values of energy and power density for future EV goals [51]. It is important to note that emerging batteries technology (also known as "beyond LIBs"), which include sodium-ion batteries (SIBs or Na-ions) or solid-state batteries using metallic lithium (SSBs or SS with Li-metal), currently show critical deficiencies. In particular, the former suffers from poor energy density and cycle life [90], while the latter faces safety concerns due to dendrite formation [91]. Therefore, they are displayed in transparency within the graphs to indicate their current technological immaturity for EV applications.

Table 2 presents the range of the main performance indicator values for commercial battery technologies and provides at the same time a comparative overview [92], [93], [94]. In contrast, Table 3 outlines the target performance requirements for battery technologies in EV applications by 2030 [51], [52]. Both tables refer to cell-level performance.

Table 2
Performance comparison of commercial battery technologies used in EVs [92], [93], [94].

	Pb-Acid	Ni-Cd	Ni-MH	Li-Ion
Used since	Late 1800s	1950	1990	1991
Specific Energy Density (Wh/kg)	30 – 50	40 – 80	60 – 100	100 – 300
Volumetric Energy Density (Wh/L)	50 – 90	60 – 180	80 – 300	200 – 700
Specific Power Density (W/kg)	10 – 100	50 – 150	100 – 1000	100 – 9000
Internal Resistance (m Ω)	≤ 100	100 – 200	200 – 300	10 – 50
Cycle Life *at 80% DoD*	200 – 300	1000	300 – 500	500 – 7000
Charge Time (h)	8 – 16	1 – 2	2 – 4	1 – 2
Self-Discharge/ Month *at 20°C*	5%	20%	30%	<5%
Nominal Voltage (V)	2	1.2	1.2	3.7 – 3.9
MCV (V)	2.4	Full charge detection by voltage signature		4.2 – 4.4
EODV (V)	1.75	1		2.5 – 3
CE (%)	≈ 90	≈ 70 (slow charge) ≈ 90 (fast charge)		≈ 99
EE (%)	70	60 – 90	75	80 – 85
Operating Temperature (°C)	-20 – 60	-20 – 60	-20 – 60	-20 – 60
Maintenance (days)	180	Not needed unless there is a problem	180	Not needed unless there is a problem
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory
Toxicity	Very high	Very high	Low	Low
Cost	Low	Moderate		High

3. Overview of LIB technologies

3.1. Working principle

The combination of its strong tendency to shed electrons and its high electrochemical potential makes Li the most important element of LIBs.

At the core of every LIB system is the individual cell, the fundamental unit responsible for storing electrical energy through electrochemical reactions. Each cell consists of four critical parts, which include two electrodes (an anode and a cathode), an electrolyte, and a separator [95]. All these components are encased in a protective casing and work together to determine the efficiency and the performance of the battery.

The electrodes consist of current collectors (i.e., Cu foils for the anode and Al foils for the cathode) coated with a mixture of active materials, conductive additives and binders. Herein, the active materials are responsible for storing and releasing energy; whereas the additives and binders improve conductivity, stability, and adhesion. Lithium ions (Li^+) move between electrodes through an electrolyte, which is typically a solution of a lithium salt in an organic solvent. At the same time, a microporous polymer membrane (i.e. the separator), is positioned between the electrodes to prevent their direct contact and, thus, to avoid internal short circuit. In particular, it selectively allows Li^+ to pass through while blocking electrons (e^-). In this way, the flow of e^-, generated by the movement of Li^+, is directed by means of the current

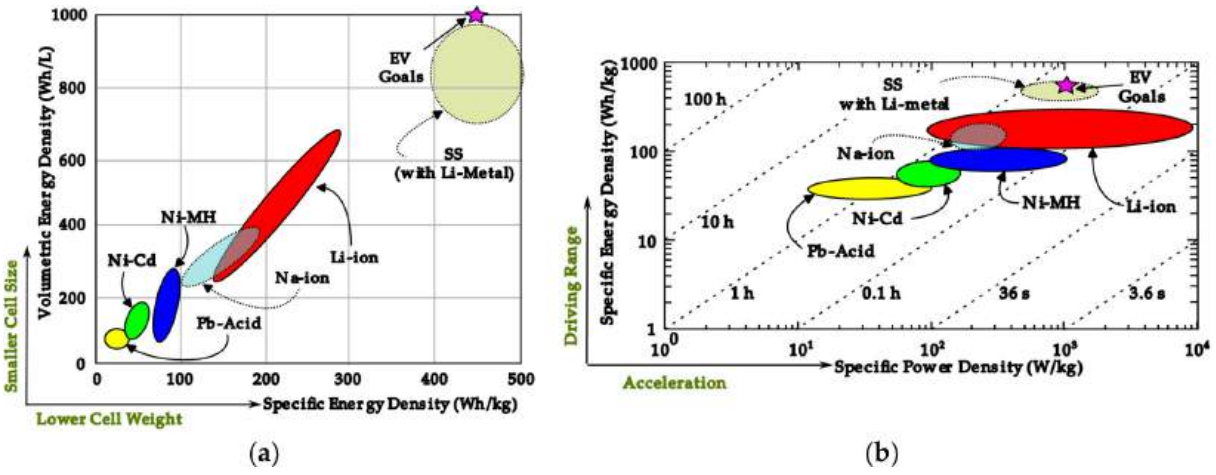

Fig. 4. Ragone plots illustrating the energy and power characteristics of commercial and emerging battery technologies for EVs: (**a**) specific energy density vs volumetric energy density; (**b**) specific power density vs specific energy density.

Table 3
Battery 2030 requirements for next-generation EV applications [51], [52].

Parameter at cell level (unit)	Condition	Target 2030 Medium Range (400 km)	Target 2030 High Range (600 km)
Specific Energy Density (Wh/kg)	0.33 C (Charge and Discharge) – 25 °C	450	450
Volumetric Energy Density (Wh/L)	0.33 C (Charge and Discharge) – 25 °C	1000	1000
Specific Power Density (W/kg)	Discharge: 180 s – 100% SoC ➔ 10% SoC – 25 °C	1000	1000
Volumetric Power Density (W/L)	Discharge: 180 s – 100% SoC ➔ 10% SoC – 25 °C	2200	2200
Charging Rate (C)	Charge: 0% SoC ➔ 80% SoC – 25 °C	3.5	3.5
Self-discharge (%)	Discharge: 100% SoC – 25 °C – 30 days	1	1
Cycle Life (-)	80% DoD – 25 °C – until EoL=80% SoH	1000	1000
Calendar Life (years)	–	10	10
Safety (hazard level)	–	≤ 4 (no fire/ rupture/ explosion)	≤ 4 (no fire/ rupture/ explosion)
Cost (€/kWh)	–	70	70

collectors of the electrodes through an external circuit where external loads can be powered or the battery recharged.

As depicted in Fig. 5, which also highlights the main materials used in LIB components, the cathode and anode active materials constitute the largest portion of the battery's weight [96], [97], [98]. This is because the operation of LIBs is based on the Li^+ intercalation (lithiation) and de-intercalation (delithiation) process where charge and discharge occur by the transfer of Li^+ and e^- between the electrodes.

The working mechanism of LIBs is illustrated in Fig. 6 using a $LiCoO_2$ /graphite cell as an example. During charging (Fig. 6a), an external voltage from a power supply causes Li^+ to de-intercalate from the cathode active material (stable chemical state), diffuse into the electrolyte, pass through the separator's nanopores, and intercalate into the anode active material (unstable condition). Simultaneously, e^- flow in the opposite direction through the external circuit to maintain electroneutrality. During discharging (Fig. 6b), when the battery is connected to a load, the process is reversed, and energy in the form of electricity is released. Specifically, e^- flow from the anode to the cathode through the external circuit where they provide power to an external load, while Li^+ move back to the stable chemical state in the cathode through the electrolyte. The charge and discharge reactions are as follows:

Cathode	*Charge*	$LiCoO_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$	(1)
	Discharge	$Li_{1-x}CoO_2 + xLi^+ + xe^- \rightarrow LiCoO_2$	
Anode	*Charge*	$6C + xLi^+ + xe^- \rightarrow Li_xC_6$	(2)
	Discharge	$Li_xC_6 \rightarrow 6C + xLi^+ + xe^-$	
Overall Reactions	*Charge*	$LiCoO_2 + 6C \rightarrow Li_{1-x}CoO_2 + Li_xC_6$	(3)
	Discharge	$Li_{1-x}CoO_2 + Li_xC_6 \rightarrow LiCoO_2 + 6C$	

From Fig. 6 above, it can be observed that the polarity of the battery depends on its state. When discharging, the anode is the negative pole (-) which loses e^- by being oxidized, and the cathode is the positive pole (+) where e^- are added by reduction. The opposite occurs during charging. Usually, the polarity of the electrodes is defined according to the process of discharge.

Even though the Li^+ intercalation and de-intercalation are known to be reversible, some losses are usually observed during the first cycle due to the formation of the Solid Electrolyte Interface (SEI) on the anode and the Cathode Electrolyte Interphase (CEI) on the cathode. These thin, complex, and disordered passivation layers form when the electrolyte interacts with the electrode active materials [99], and play an important role in the cycle life of the battery, a characteristic that is mandatory for EV applications [100]. Specifically, the SEI and CEI allow Li^+ transport while block at the same time e^- flow. This in turn prevents further electrolyte decomposition and ensures electrochemical stability [101]. However, their formation consumes Li^+ and electrode active materials, resulting in a loss of battery capacity, increased internal resistance and reduced power output [102], [103].

3.2. Classification

LIBs can be classified into [75]:

- Energy-Optimized or High-Energy (HE) LIBs;
- Power-Optimized or High-Power (HP) LIBs.

HE LIBs provide high energy densities but low power densities. As a result, among the different types of EVs, they are well suited for BEVs, where the driving range is a key factor. On the other hand, HP LIBs offer

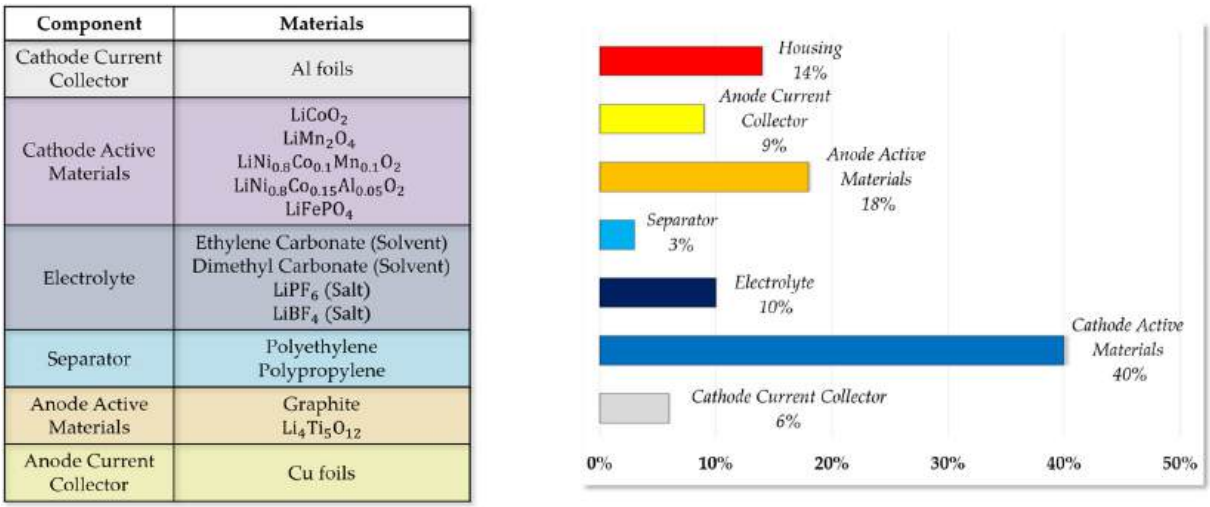

Fig. 5. Main material components and their weight fractions in LIB cells.

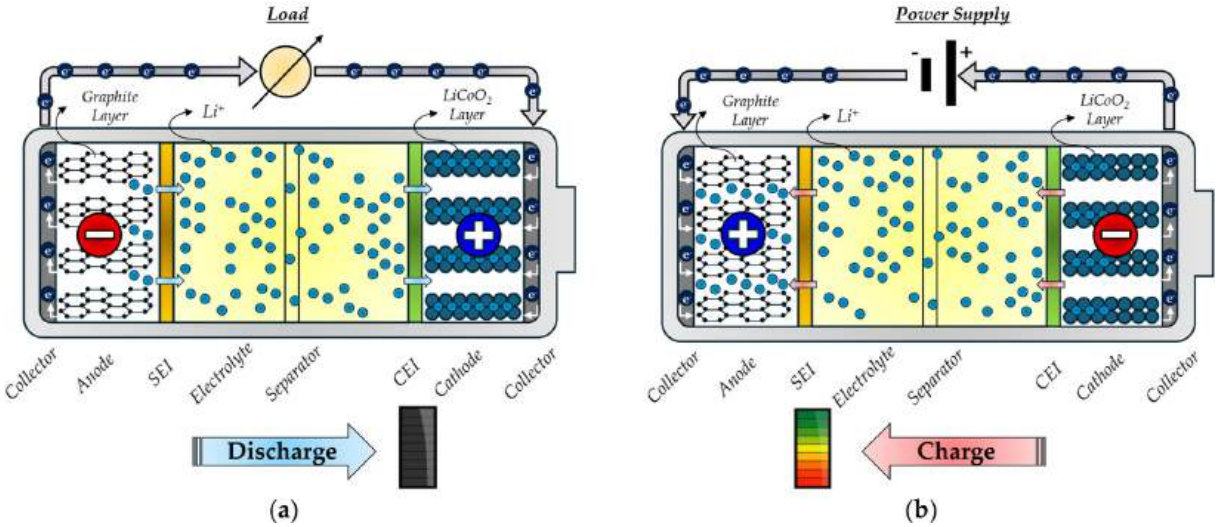

Fig. 6. Working principle of LIBs: (**a**) Discharging process; (**b**) Charging process.

high power densities and can deliver very high currents (high C-rates), making them ideal for HEVs, which demand rapid energy delivery during acceleration (discharging) and fast energy storage during braking (charging).

3.3. Cell designs

The design of LIB cells is driven by application-specific requirements (i.e., performance, safety, recyclability and cost) and involves several parameters, which include electrolyte composition, electrode porosity, coating weight, collector and tag thickness, assembly methods, and cell format [104]. The optimal combination of these parameters depends on the goal, i.e., maximizing power density or energy density. HP LIBs, for example, require minimizing the resistances of cell components (electronic, ionic, and thermal). This can be obtained through thin coatings, smaller and lighter collectors and tags, high electrode porosity, and the use of robust conductive materials [104], [105]. In contrast, HE LIBs, which aim to optimize the ratio of active material to the total electrode volume, necessitate thicker coatings, larger collectors and tags and lower electrode porosity [104]. For example, HE LIBs used in EVs typically have single-sided electrode coatings, which range from 50 to 80 μm [106].

Fig. 7(a-c) shows the three most used LIB cell formats for EV applications [107]. Cylindrical cells (Fig. 7a), characterized by a high degree of standardization and lower manufacturing costs [108], offer good energy densities (specific ≈ 250 Wh/kg and volumetric ≈ 700 Wh/L) thanks to the good volume utilization through wound electrodes [109]. Common cylindrical cell formats include the 18650 (mass ≈ 40 g, volume ≈ 16 mL, capacity ≤ 3.4 Ah) and the 21700 (mass ≈ 60 g, volume ≈ 23 mL, capacity ≈ 5 Ah) [110]. The metallic casing and round format allow them to withstand elevated internal pressure and mechanical stress [111]. However, due to their low capacity and small volume, these cells can store less energy compared to other formats [112]. This improves heat dissipation, but it also means that a large number of cells (often not well distributed within the available space) is required to assemble battery packs for EV applications [113], [114]. Larger tabless cylindrical formats, such as 4680 (mass ≈ 355 g, volume ≈ 133 mL, capacity ≈ 26 Ah [115]) and the 4695 (mass ≈ 450 g, volume ≈ 140 mL, capacity ≈ 36 Ah [104]), could solve this issue, as they have the potential to reach higher energy and power densities [113], [116]. As a result, manufacturers like BMW [117], Nio [118], GM [119], Mazda [120] and Subaru [121] have announced plans to adopt these formats for next-generation EVs.

Prismatic cells (Fig. 7b) feature a hard-case, typically Al or stainless steel, housing, which provides good mechanical stability and durability [122]. The rectangular shape and solid casing contribute to good integrability in modules and packs, making them suitable for direct integration (cell-to-pack concept).These arrangements eliminate the modular design feature of traditional batteries, allowing cells to be directly incorporated into the pack. As a result of this paradigm change, production costs and total mass are decreased, making electric vehicles (EVs) more affordable and energy-efficient [123].. There are two main types of prismatic cells. Smaller, thinner cells (thickness ≈ 12 – 36 mm, length ≈ 400 mm), which can reach nominal capacities up to 100 Ah, and larger, thicker cells (thickness ≈ 80 mm, length ≈ 400 – 900 mm) with nominal capacities of around 150 Ah [104]. The high nominal capacities and easy installation allow for high packing density [107]. However, the heat dissipation of prismatic cells is poor, which makes the cooling process challenging [53]. Additionally, these cells present the worst energy density compared to other formats. To enhance energy density, manufacturers are increasingly adopting stacked electrode assembly techniques and specific cell chemistries, allowing them to close the gap with the other formats (specific ≈ 250 Wh/kg and volumetric ≈ 650 Wh/L) [109]. These developments are pushing automakers such as Ford [124], Toyota [125] and Mercedes [126] to shift towards prismatic cells for future EV generations.

Pouch cells (Fig. 7c) are known for their lightweight and flexible polymer foil housing [107]. This design and the good storage nominal capacity of around 100 Ah enable them to achieve high energy densities (specific ≈ 300 Wh/kg and volumetric ≈ 670 Wh/L) [104], [110]. Another important advantage of these cells (thickness ≈ 15 mm, length > 500 mm, volume ≈ 500 mL) is the greater ease of recycling at the EoL [104], [109]. However, the flexible casing suffers from relatively poor mechanical stability. This necessitates battery modules with a robust design to protect them from damage [127]. In addition to this, the polymer enclosure limits heat dissipation and reduces resistance to high internal pressures compared to cylindrical and prismatic cells [104], [109]. Despite these aspects, many EV manufacturers (i.e., Renault, Hyundai, Kia) utilize pouch cells, and this cell format is considered promising for the future [128], [129].

To obtain desired voltage and capacity, hundreds to thousands of cells are typically combined (in parallel and in series) first within modules and then in a pack, as schematically shown in Fig. 7d [130]. For instance, a Tesla EV is powered by approximately 7000 cylindrical cells, which provide a total voltage of 400 V and a capacity 212.5 Ah → (85 kWh) [131]. However, since efficiency in design has become a priority in recent years, the cell-to-pack (CTP (Fig. 7e) or cell-to-chassis (CTC) concepts (Fig. 7e) are now considered key advancements in EV battery

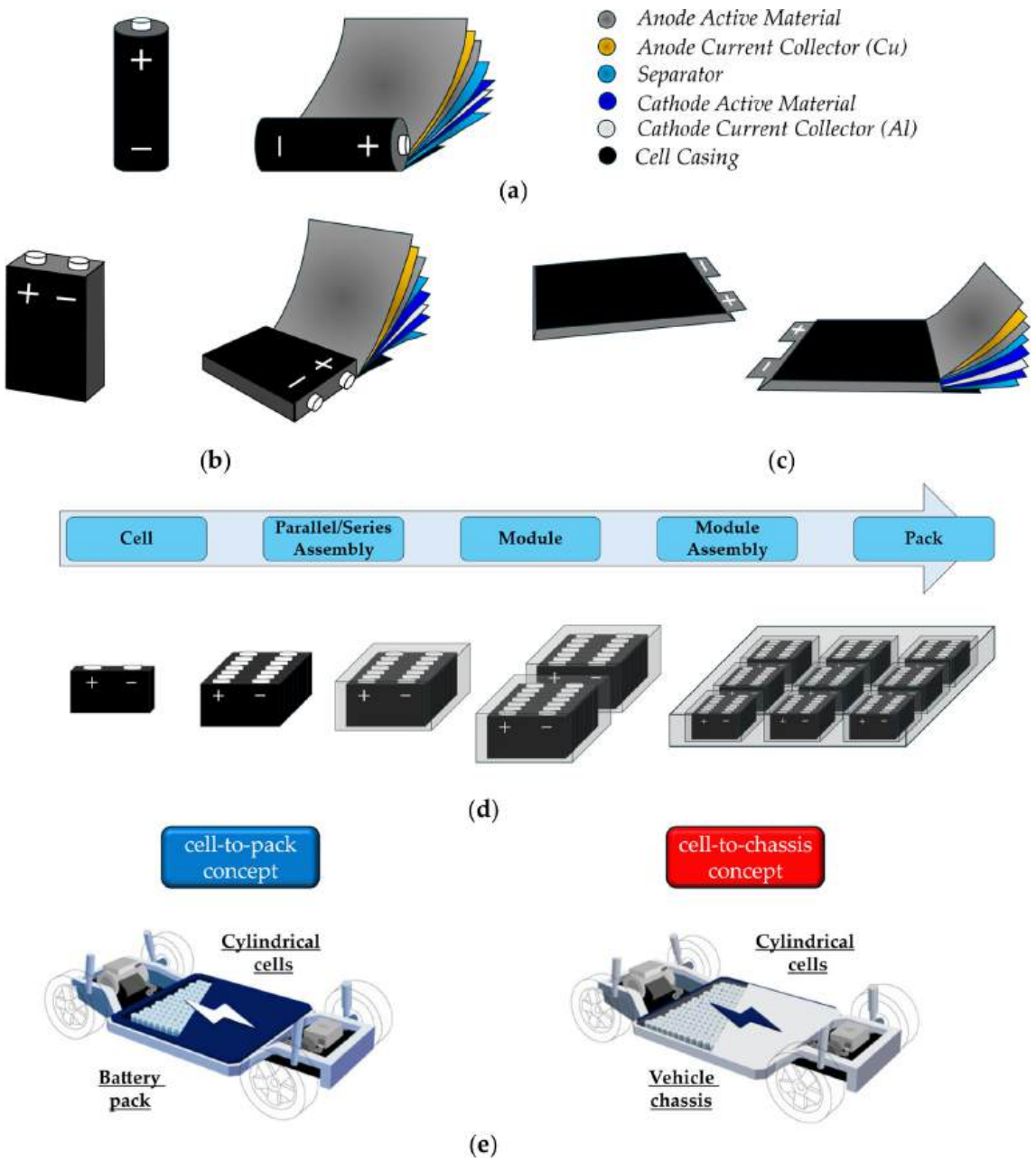

Fig. 7. LIB cell types used for EV applications: (**a**) Cylindrical; (**b**) Prismatic; (**c**) Pouch. (**d**) Schematic representation of the relationship between cell, module and pack with prismatic cells; (**e**) cell-to-pack concept and cell-to-chassis concepts with cylindrical cells.

technology [132]. By removing the intermediate module stage, these approaches enhance volumetric energy utilization, reduce structural redundancy, and lower both production costs and overall mass. In particular, while CTP optimizes packaging efficiency, CTC integrates the cells directly into the vehicle chassis, maximizing space utilization and enabling higher driving ranges [133]. At the same time, this level of integration raises new challenges related to crash safety, thermal management, repairability, and standardization, which remain critical aspects for large-scale implementation [133], [134].

3.4. Performance characterization

3.4.1. Polarization curve

The polarization curve is one of the most commonly used methods to illustrate the relationship between voltage output and current density of LIBs. By showing how the operating voltage varies with different current levels, it offers crucial information about LIB theoretical performance [135]. In addition to this, this curve can also be used to analyse the contribution of various polarization losses, that occur when the battery is under load. This in turn enables the operating voltage to be differentiated form theoretical OCV [136].

The polarization losses can be broken down into three main types: activation losses, ohmic losses, and mass transport losses [137], [138]. Activation losses, most noticeable at low current densities, are primarily influenced by the energy required to initiate electrochemical reactions, such as the energy barrier that Li^+ must overcome at the electrode-electrolyte interface. Ohmic losses, which result in a voltage drop proportional to the flowing current, are caused by the inherent resistance of cell components. Mass transport losses, instead, are mainly due to resistance to Li^+ transport through the electrolyte and are evident at high current densities.

Fig. 8 aims to illustrate these relationships. Specifically, Fig. 8a

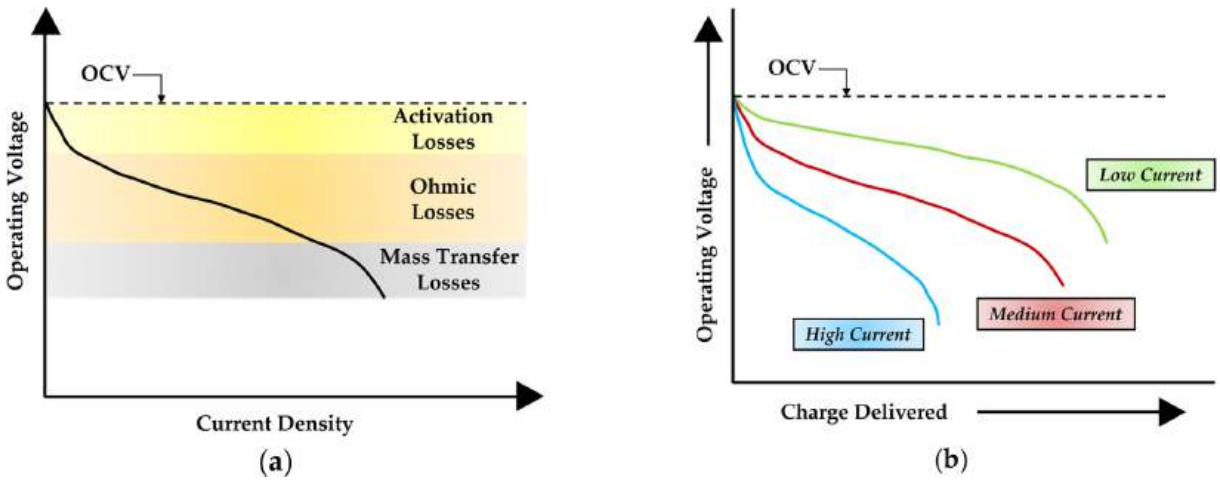

Fig. 8. (**a**) A typical polarization curve of a LIB; (**b**) Effect of current on the operating voltage [137], [138].

shows a typical LIB polarization curve, where the combined impact of activation, ohmic, and mass transport losses is represented as the deviation from the theoretical OCV [138]. In addition, since these losses are current-dependent, Fig. 8b highlights how the associated voltage drop increases with higher output current [137]. It should be noted that Fig. 8 is a theoretical illustration, intended to conceptually highlight the different types of polarization losses and their current-dependent behaviour, which is essential for linking electrochemical processes to the observed performance.

3.4.2. *Discharging and charging curves*

When shifting from theoretical aspects to practical applications, it is important to examine the discharging and charging curves of LIBs. By analysing the changes in operating voltage and current during the two processes, important information about key performance parameters such as battery capacity, energy output, lifetime, efficiency and safety can be obtained.

Since the output current drawn from a LIB significantly impacts the internal losses, it is an important parameter that needs to be analysed for comparing battery performance. Fig. 9a shows different discharge curves for a typical LIB cell under constant current (CC) conditions, at various C-rates and at an operating temperature of 23°C, presented in an operating voltage vs capacity plot [139]. The discharge curves can also be represented with current on the vertical axis and discharge time, energy density, or SoC on the horizontal axis. It is evident that the operating voltage decreases throughout the discharge process for all the different discharge curves until it reaches the EODV. This voltage value, which LIB manufacturers commonly set between 2.5 V and 3 V, depending on the chemistry [140], determines the battery capacity for a given C-rate. The higher the C-rate, the lower the battery capacity [6]. Fig. 9a also shows how the discharge rate impacts the operating voltage due to the polarization losses that were previously discussed.

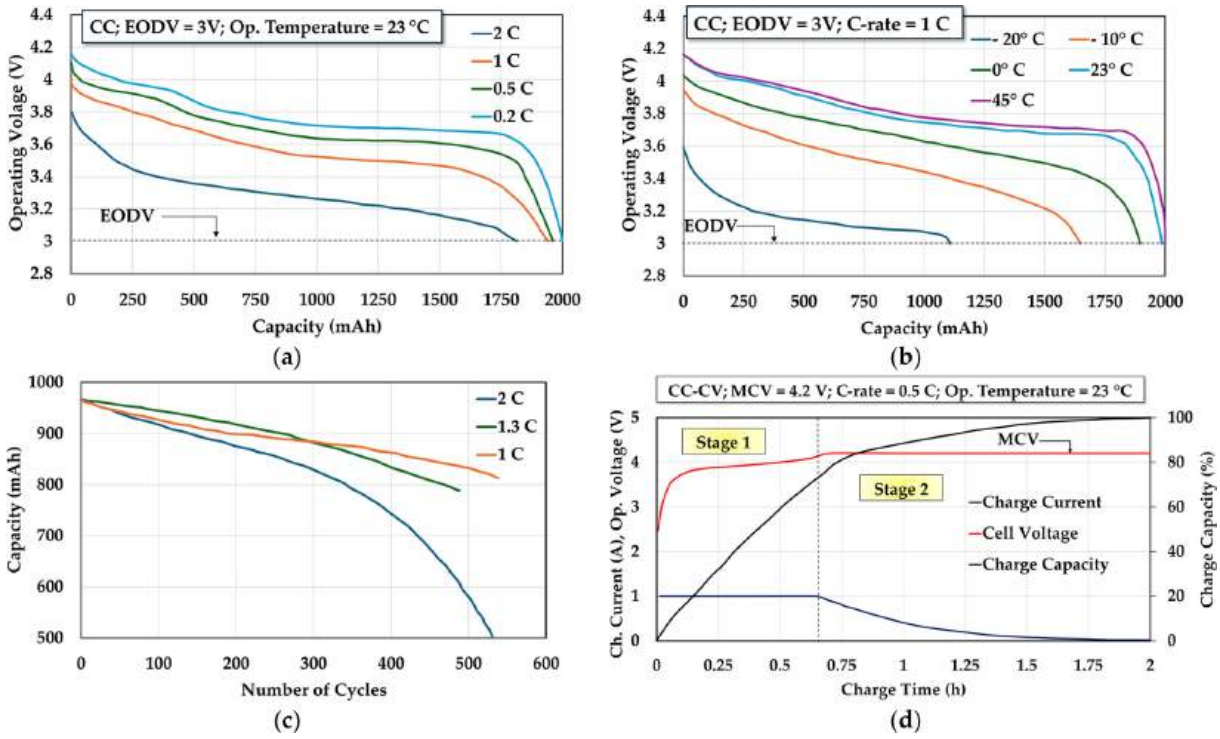

Fig. 9. Typical LIB cell: (**a**) Discharge curves at different C-rates and 23 °C; (**b**) Discharge curves at different operating temperatures and 1 C; (**c**) Capacity retention and number of cycles at different C-rate; (**d**) Charging curve at 0.5 C and 23°C.

Specifically, as the C-rate increases, the increased internal resistance causes the operating voltage to drop more sharply, lowering the battery's maximum capacity and thus the amount of energy that can be produced. This can also be noted analysing the area under the discharge curve which corresponds to the energy that a battery provides. As a result, a flatter discharge curve is preferred for EV applications as it helps maintain the operating voltage constant during the discharge processes [141]. Nevertheless, a sloping curve also has advantages, particularly in simplifying the estimation of the SoC [142].

The performance of LIBs depends not only on the rate at which they are discharged, but also on the operating temperatures. LIBs typically operate between -20°C and 60°C [139], with optimal range between 15°C and 35°C [143]. Fig. 9b illustrates different discharge curves for a typical LIB cell at various temperatures and at a C-rate of 1 C [144]. In colder countries such as Canada and Russia, where winter temperatures can fall below 0°C, the activation and mass transfer losses during battery discharge operations become relevant [145], [146]. This accelerates performance degradation and reduces the energy and power output [147]. High internal temperatures, on the other hand, which typically come due to high discharge rates [148], can result in power loss [149], capacity fading [150], increased internal resistance [151], and a shorter battery lifetime [152].

Regarding this last concept, Fig. 9c shows how many cycles a LIB cell can withstand when discharged at different C-rates [153]. The battery is subjected to much more stress at a 2C discharge rate than at 1C, limiting the number of cycles to roughly 450 before its capacity falls to half of its starting value.

The C-rate is also a critical factor in the charging process. In general, faster charging results from higher current produced by a higher C-rate. However, although a higher C-rate accelerates the process, it generates internal heat that reduces cycling stability and shortens the lifetime of the battery [154]. Manufacturers of LIB cells usually advise charging at a C-rate between 0.5C and 1C with ambient temperature condition in order to extend battery lifespan, so generating a total charge time of roughly 1–2 hours [155]. At this charging rate and temperature, the EE is about 97%, and the cell remains cool throughout the process [156].

Fig. 9d illustrate the typical charging characteristic of a LIB cell in terms of operating voltage, current, and capacity [139]. The charging process generally follows the constant current-constant voltage (CC-CV) method, which is widely recommended for optimal performance [157]. The battery initially charges at a constant current (Stage 1). Specifically, at the beginning of this stage, the voltage increases steeply as Li^+ rapidly move from the cathode to the anode thanks to the low cell internal resistance. As a result, an efficient energy storage is obtained. As charging continues, the voltage rise slows due to polarization effects. The activation and mass transfer losses, limits Li^+ movement and reduces energy storage efficiency. Once the battery reaches its designated MCV, typically between 4.2 V and 4.4 V depending on the chemistry [140], the charging mode transitions to a constant voltage phase (Stage 2), where the current exponentially decreases. Charging is considered complete when the current drops below C/10 [139]. The trickle charge phase in Stage 2 is useful to prevent possible overcharging, which can lead to overheating, electrolyte breakdown, or structural damage. It also ensures uniform charge distribution across all battery cells. Due to this behaviour, EV manufacturers often advise against charging to a full 100%. Instead, a "charge-and-run" method is commonly used, where the battery is rapidly charged to approximately 80% in one hour or less, avoiding the slower Stage 2 charging phase [155].

3.5. Degradation mechanisms

LIB degradation is a highly complex phenomenon that significantly affects the safety and performance of EVs. It can be defined as an irreversible loss of the ability of a battery to store energy (capacity loss) or alternatively a permanent reduction in the rate at which energy can be delivered or accepted (power loss) [158], [159]. Electrochemical parameters such as internal resistance, operating voltage, SoC and SoH are commonly used to monitor battery degradation [160].

In its life, the capacity loss of a typical LIB follows three distinct phases, which are illustrated in Fig. 10a [161]:

- Stabilization: This initial phase is characterized by a rapid decrease in battery capacity due to the formation of the SEI layer on the anode surface (Fig. 10b). The latter, by consuming electrolyte and Li^+, leads to the initial capacity drop [102]. Many researchers consider the SEI layer and its stability to be the main cause of ageing in this electrode [162], [163].
- Pseudo-Linear Degradation: Although battery degradation is a non-linear process, during this phase, if usage conditions do not change drastically, the capacity will decrease roughly linearly until it reaches the so-called “knee point” [164]. This point corresponds to the minimum capacity level or EoL, namely the point where the battery retains 80% of its nominal capacity [78], [79].
- Sudden Death: At the "knee point," the internal resistance of the battery increases to almost 1.5 times its original value, and a strong exponential capacity loss per cycle takes place [164]. This phenomenon, known as the sudden death effect, results from multiple internal degradation mechanisms which become ever increasingly relevant [165].

Battery degradation can occur during charging, discharging, or even while the battery is at rest. This aging process is driven by various physical and chemical mechanisms that impact different cell components, including the electrodes [166], [167], electrolyte [168], and separator [169] as well as the electrode/electrolyte interface [170]. Fig. 11 shows some of the most commonly reported degradation mechanisms in LIB cells [158].

Referring to Fig. 11, which shows a simplified schematic of a typical LIB cell with a graphite particle as the anode and a transition metal oxide as the cathode, the major degradation mechanisms associated with LIBs can be summarized based on those occurring in the anode, and cathode:

- Anode degradation mechanisms:
  - ➢ SEI layer growth and formation: In the charged state, the operating voltage of graphitic anodes (lower than 0.3 V versus Li/Li^+ [171]) is below the electrochemical stability window of the electrolyte. As a result, during the first cycle of the cell, decomposition of both the electrolyte (including Li^+) and the anode active material occurs at the electrode/electrolyte interface [172]. The products of this decomposition form a passivating film on the anode surface known as the SEI [101]. This layer, which is ionically conductive and electrically insulated, protects the electrolyte from further reduction and the anode from corrosion [173]. However, it increases cell resistance and leads to self-discharge and capacity fade due to loss of Li^+ [102]. In addition to this, it is important to note that, the rate of generation of the SEI layer increases with temperature [151].
  - ➢ Increased SEI thickness and density/Graphite exfoliation/Particle cracking/Electrical contact loss/Electrode porosity reduction/Transition metal dissolution and precipitation: Unfortunately, the SEI layer does not have the properties of a true solid electrolyte for Li^+. Other charged (cathode materials) and neutral (electrolyte solvent) species can still diffuse through it, increasing its density and thickness [159]. The intercalation of Li^+ and their solvation shell between graphene sheets (a process known as graphite exfoliation) results in the distortion of the anode structure, particle cracking and electrical contact loss [174]. This occurs as a result of gas evolution caused by the reductive decomposition of the electrolyte and, in turn, leads to a reduction in electrode porosity [174]. Additionally, at high temperature and high SoC, transition metal oxide cathodes suffer from transition metal dissolution (such as Fe, Mn or Co) into the electrolyte

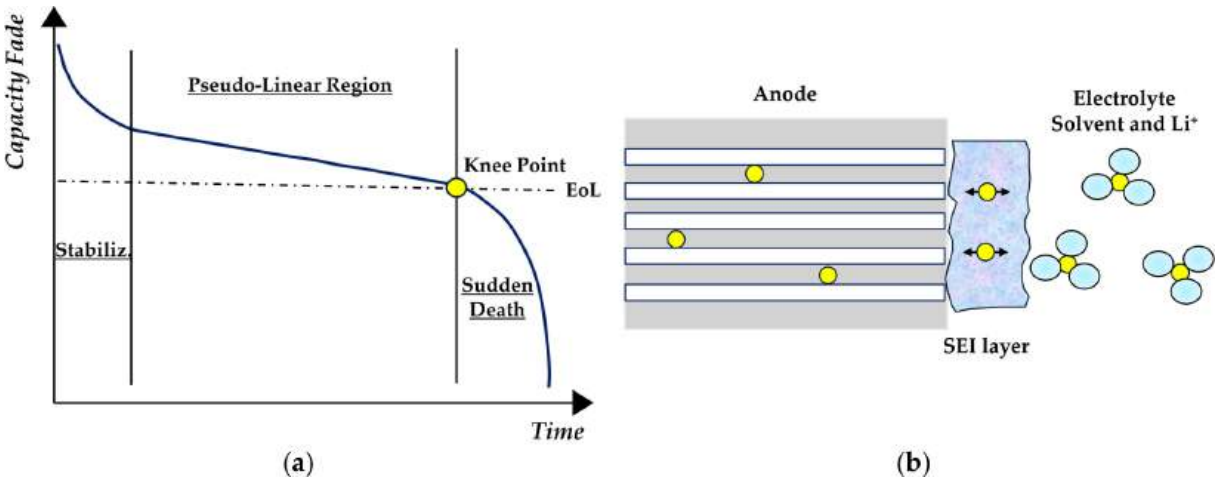

Fig. 10. Typical capacity loss trend of LIBs under stable usage conditions; (b) Growth and formation of the SEI layer.

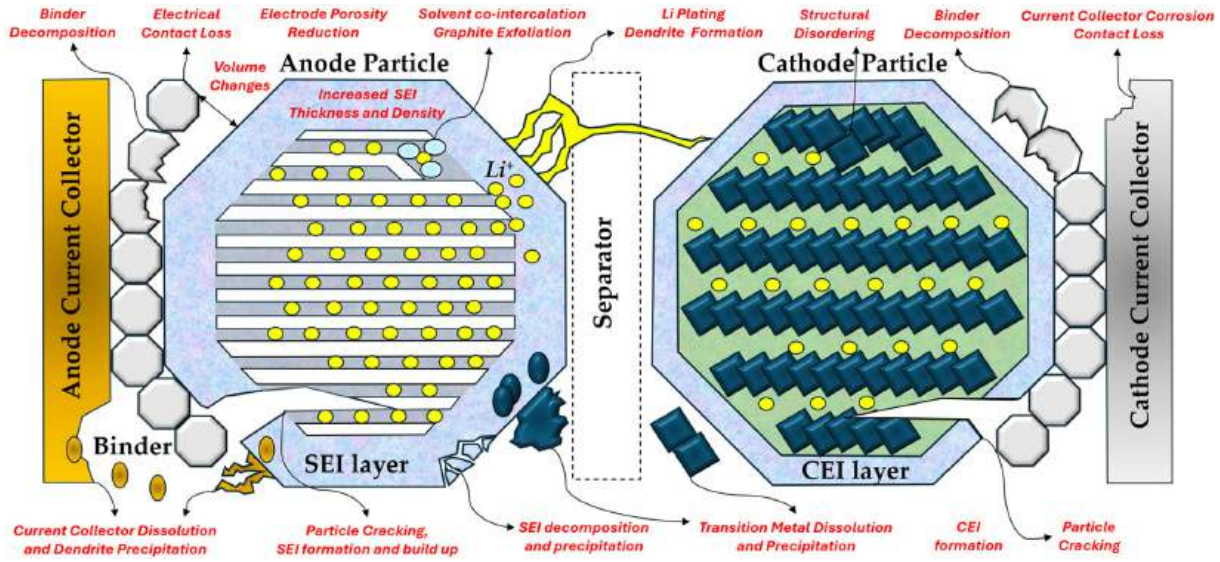

Fig. 11. Major degradation mechanisms in LIBs.

[175]. These dissolved metals can precipitate on the anode surface and cause dendrite growth (i.e. branched and sharp structures), which in turn can pose serious safety risks [176].

- ➢ Volume changes/SEI decomposition and precipitation: The anode (graphite) volume changes (approximately 10% [171]) during Li^+ intercalation/deintercalation cause the SEI to become unstable and crack [176]. Additionally, the fatigue due to repeated expansion and contraction of the anode also causes loss of contact with electrically conductive binders [159], [177].
- ➢ Li plating and dendrite formation: The intercalation operating voltage of graphite is close to that of Li-metal. During charging, at low temperatures and high SoC, the slow Li^+ diffusion can cause Li-metal plating on the anode surface, which in turn leads to the formation of long, pointy Li-metal branches (i.e., dendrites) [178], [179]. This results in an important loss of available Li^+ from the electrolyte. Additionally, this Li-metal dendrites can puncture the separator, enabling electrical conduction between the anode and the cathode, or in order words, creating a short circuit [180]. When this happens, a large current flows within the cell, which can cause in certain situations thermal runaway. Thermal runaway is a chain reaction that causes the temperature to rise in an uncontrolled manner, leading to severe safety risks, such as battery fires, explosions, or the release of toxic fumes [181].
- ➢ Current collector dissolution and dendrite precipitation: At very low SoC, the Cu current collector can fall outside of its electrochemical stability window and thus dissolve into the electrolyte. In particular, when Cu dissolves, it can later re-deposit onto the anode surface during the next cycle, forming metallic dendrites and increasing the safety risk [159].
- ➢ Binder decomposition/Electrical contact loss: At high temperatures, the binders react with the electrolyte and decompose. This results in a loss of electrical contact and an increase in electrical resistance [159].

- Cathode degradation mechanisms:
  - ➢ CEI formation: The cathode operates within a voltage window (2.5-5 V vs. Li/Li^+ [171]), which unlike the anode, is within the electrochemical stability window of the electrolyte. Therefore, it does not typically cause electrolyte decomposition [172]. However, during the first cycle, at high SoC, the active material of the cathode reacts with the electrolyte resulting in the formation of the CEI film on its surface [182]. This film, which thickness increases with temperature, has much less influence on the battery performance degradation compared to the SEI layer [175].

- ➢ Structural disordering/Particle cracking/Electrical contact loss: During battery operation, the cathode is subjected to high mechanical stress due to the intercalation and deintercalation of Li^+. This stress can cause particle cracking, structural disorder, and loss of contact with conductive binders and thus with the current collector [159].
- ➢ Current collector corrosion and electrical contact loss: As described for the Cu current collector (anode), the Al current collector (cathode) also experiences dissolution into the electrolyte at very low SoC. As a result, its electrical conductivity decreases and its electrical resistance increases [175].
- ➢ Binder decomposition/Electrical contact loss: Like the anode, at high temperatures, the binders react with the electrolyte and decompose. Once again, this results in a loss of electrical contact [175].

The measurable physical effects of these degradation mechanisms on the cell can be summarised in terms of five degradation modes, each contributing to losses in capacity and power [158]:

- Loss of cyclable Li^+;
- Loss of anode active material;
- Loss of cathode active material;
- Reduced kinetics;
- Increased resistance.

Fig. 12 provides a LIB degradation map that illustrates the degradation mechanisms, their causes, effects, and links to degradation modes.

4. Research advancements in LIB electrode materials

The electrodes, both the cathode and anode, are the most important components of LIBs, as they govern the temporary storage and release of Li^+ during charge and discharge cycles. Their chemical composition and structural properties notably impact recyclability and key performance parameters, including energy and power density, capacity, rate capability, cycle life, chemical/mechanical/thermal stability, safety and cost [183], [184].

To meet the LIB performance targets for next-generation EVs [185], extensive research has been focused on improving electrode materials, in order to enhance the overall efficiency of the cells. However, it is important to note that these advancements are only practical if the materials remain cost-effective and widely available.

4.1. Cathode active materials

Cathode active materials represent the most important cost component of LIBs, accounting for nearly half of the total cost of a battery cell [186], [187]. According to their operating mechanism, cathode materials can be divided into two categories: conversion (such as metal halides) and intercalation (such as transition metal oxides and polyanion compounds) [171].

This review will focus solely on intercalation cathode materials

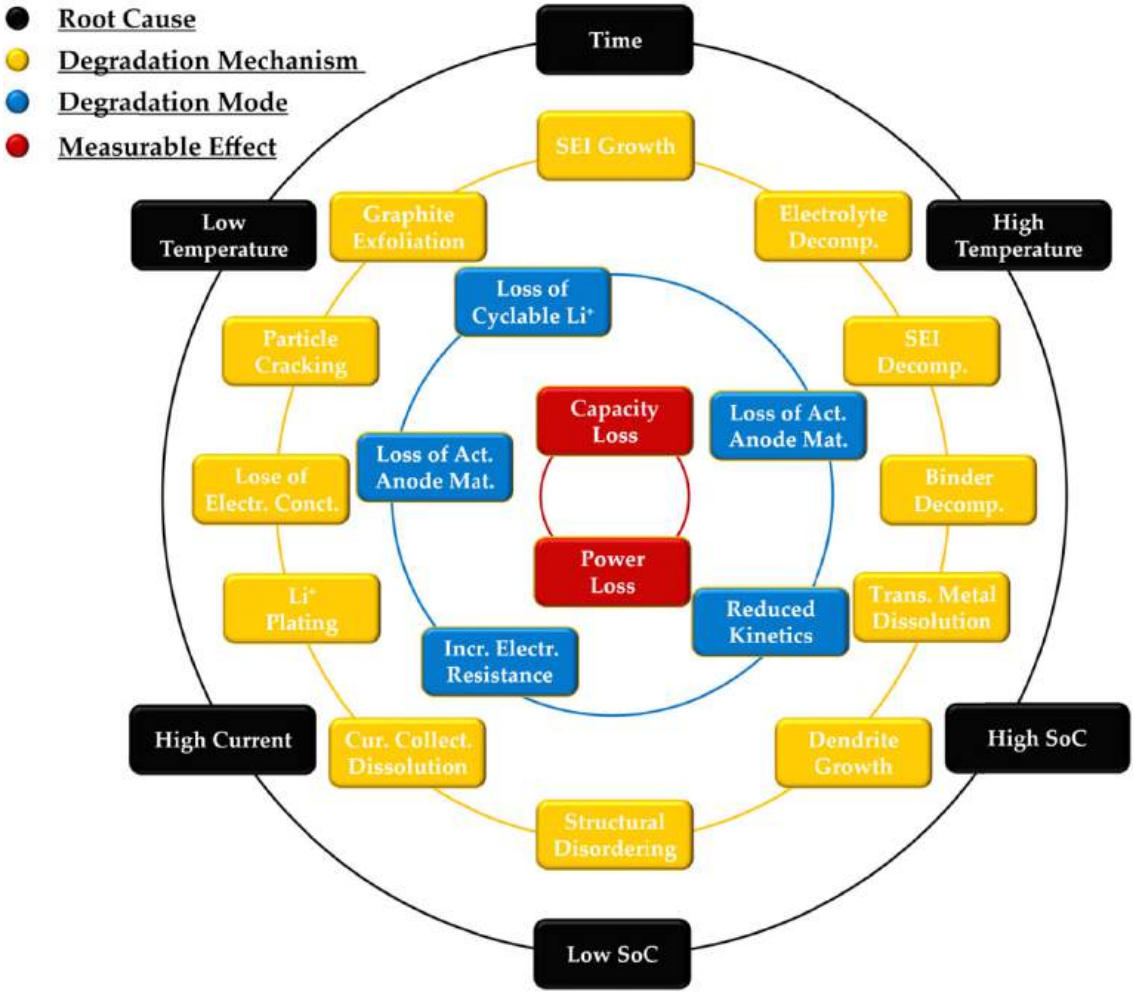

Fig. 12. Root causes and measurable effects of LIB degradation.

(ICMs), as conversion cathode materials (CCMs) have not yet been commercialized due to several challenges. Although CCMs offer high theoretical specific capacity, their practical application is hindered by issues such as intermediate operating voltage (typically below 3 V vs (Li/Li^+)), high voltage hysteresis (up to 2 V), poor electronic conductivity and ionic mobility, significant volume expansion (up to 100%) during lithiation and delithiation, electrolyte decomposition and mechanical degradation [171]. For further details please refer to [171].

4.1.1. Intercalation cathode materials

Intercalation cathode materials (ICMs), which can be composed of mixed oxides or polyanionic compounds applied to an Al current collector, are the most common type of cathode materials in LIBs. By serving as host structures, such cathode materials allow Li^+ to intercalate and deintercalate reversibly. This results in efficient energy storage and release during battery charging and discharging operations [171].

ICMs in LIBs usually include Li combined with transition metals like Co, Ni, Mn, and Fe, and O_2 in transition metal oxides or polyanionic groups like $\left((PO_4)^{3-}\right)$ in polyanionic compounds [171]. Moreover, Al is commonly added to improve thermal stability and structural integrity even though it does not directly participate in electrochemical reactions [188]. Depending on their composition, ICMs can have different crystal structures, including layered, spinel, and olivine, each of which influences battery electrochemical performance [171], [189].

As previously specified, ICMs can be divided into two main groups:

- Transition metal oxides:
  - ➢ Layered structure ($LiMO_2$, M = Co, Ni, Mn, Al):
    - ✓ Lithium Cobalt Oxide ($LiCoO_2$) or (LCO);
    - ✓ Lithium Nickel Oxide ($LiNiO_2$) or (LNO):
    - ✓ Lithium Nickel Cobalt Manganese Oxide ($LiNi_{(1-x-y)}Co_xMn_yO_2$) or (NCM);
    - ✓ Lithium Nickel Cobalt Aluminium Oxide ($LiNi_{(1-x-y)}Co_xAl_yO_2$) or (NCA);
    - ✓ Lithium Nickel Manganese Cobalt Aluminium Oxide ($LiNi_{(1-x-y-z)}Mn_xCo_yAl_zO_2$) or (NCMA).
  - ➢ Spinel structure (LiM_2O_4, M = Mn, Ni):
    - ✓ Lithium Manganese Oxide ($LiMn_2O_4$) or (LMO);
    - ✓ Lithium Manganese Nickel Oxide ($LiMn_{1.5}Ni_{0.5}O_2$) or (LMNO).
- Polyanion compounds:
  - ➢ Olivine structure ($LiMPO_4$, M = Fe, Mn):
    - ✓ Lithium Iron Phosphate ($LiFePO_4$) or (LFP);
    - ✓ Lithium Manganese Iron Phosphate ($LiMn_xFe_{1-x}PO_4$) or (LMFP).

In order to make a standardized comparison of electrode materials, the electrochemical potentials are indicated with respect to Li-metal, which gives a fixed reference potential of zero (i.e., Potential V vs. Li/Li^+). Typically, ICMs have a high average operating voltage, ranging from 3 V to 5 V (vs. Li/Li^+) [171]. Despite this, a significant drawback is their generally low practical specific capacity, which is less than 250 mAh/g [171], [189]. For some of the most popular ICMs, Fig. 13a shows the approximate range of practical specific capacity and average operating voltage (vs. Li/Li^+), while Fig. 13b shows their typical discharge curves [93], [104], [171].

Commercial LIBs, which use these ICMs, achieve a specific energy density between 100 and 300 Wh/kg. However, with a theoretical limit of up to 1000 Wh/kg [190], ongoing research focuses on enhancing ICM storage capacity and operating voltage, since energy density is directly influenced by both. Improving these parameters is very important, especially for EVs where an extended driving range is a key factor. To illustrate this potential, Fig. 13a also highlights the specific energy density that LIBs could reach in the future through advancements in ICM performance [191], [192], [193], [194], [195], [196], [197], [198], [199], [200].

4.1.1.1. Transition metal oxides

4.1.1.1.1. Lithium cobalt oxide (LCO). First introduced by Goodenough in 1980s [201] and later commercialized by SONY in 1991 [202], LCO is one of the most widely used layered transition metal oxide cathode materials in LIBs. Its hexagonal crystal structure, with alternating layers of Co and Li, contributes to its high theoretical specific capacity (274 mAh/g) and volumetric capacity (1363 mAh/cm^3) [203], [204]. These characteristics, along with low self-discharge, high discharge voltage, and stable cycling performance, have made LCO suitable for application in portable electronics and early generations of EVs, such as the Tesla Roadster and Smart ForTwo [190].

Despite these advantages, LCO presents also issues that include high production costs and poor thermal stability. The former are due to Co dependence, while the latter raises safety concerns [205], as in the case of the Boeing 787 battery fires in 2013 [206]. In addition to this, deep cycling (delithiation above 4.2 V) leads to structural distortions, faster performance degradation and reduced cycle life [207]. Furthermore, LCO cannot handle excessive charge and discharge currents [208]. As a result, it needs protection against overheating and stress, with safe operation generally limited to a charge and discharge rate of around 1C [209].

To address these problems, research has focused on material modifications, which include metal doping (Mn, Al, Fe, Cr) [210], [211], [212] and oxide coatings (Al_2O_3, B_2O_3, TiO_2, ZrO_2) [213]. Oxide coatings have proved to be very effective in improving thermal stability and cycle life due to reduced side reactions with the electrolyte. Nevertheless, the high costs and supply chain issues associated with Co have driven the search for alternative ICMs [214].

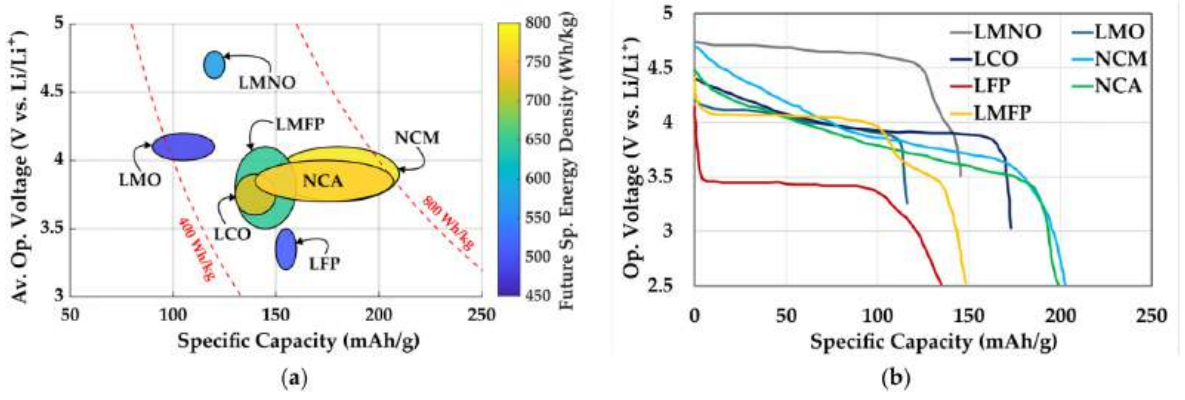

Fig. 13. ICMs: (**a**) Approximate range of average discharge operating voltage (LivsLi$^+$), practical specific capacity and future specific energy density; (**b**) typical discharge profiles [93], [104], [171], [191], [192], [193], [194], [195], [196], [197], [198], [199], [200].

4.1.1.1.2. Lithium nickel oxide (LNO) – lithium nickel cobalt manganese Oxide (NCM) – lithium nickel cobalt aluminium oxide (NMA) – lithium nickel manganese cobalt aluminium oxide (NMCA). LNO, NCM, NMA and NMCA are layered transition metal oxides, similar to LCO. With 100% Ni content, LNO offers a high theoretical specific capacity of 275 mAh/g, which makes it an attractive low-cost alternative to Co-based ICMs. However, its practical application is limited by Li^+ diffusion blockage, as Ni^{2+} tends to occupy Li^+ sites. In addition to this, LNO suffers from poor thermal stability and mechanical degradation which results in a reduced durability [215], [216]. To address these issues, three strategies have been employed. First, substituting part of the Ni with Co reduces cation disorder and improves both electronic and ionic conductivity [217]. Second, doping with Mn enhances structural stability [218]. Third, doping with Al improves thermal stability and boosts electrochemical performance [219].

As a result, NCM and NCA ICMs have been developed. In both cases, Ni-ions serve as the active redox species. The other elements (i.e., Co and Mn in NCM, and Co and Al in NCA) enhance conductivity and stability, but they do not participate in the electrochemical reactions.

The first commercially relevant NCM cathode material was NCM111 ($LiNi_{0.33}CO_{0.33}Mn_{0.33}O_2$). This ICM presented a well-balanced combination of energy density, stability, and safety, making it suitable for use in early EVs [220]. Over time, research has focused on increasing Ni content to enhance energy density and reduce the dependence on the expensive Co. This has led to a transition from low-to-medium Ni-content compositions (30 – 70%) to high-Ni formulations like NCM811 and NCM9.5.5. In this latter the Ni-content exceeds 90%. These advanced ICMs can achieve specific energy densities beyond 750 Wh/kg and maintain structural integrity [221], [222]. Due to its strong combination of energy density, fast charging capability, and long cycle life, NCM ICM has become the preferred choice in LIBs for EV applications [223]. Future advancements, such as Li-rich and Mn-rich NCM (LMR-NCM), aim to further increase energy density. However, a major drawback of NCM is its high cost, which is due to the presence of Ni and Co. Despite this, it remains more affordable than LCO [222].

Like NCM, NCA delivers practical specific capacity (around 200 mAh/g), good rate performance, and long cycle life, making it a key choice for Panasonic batteries in Tesla EVs [171]. For this ICM as well, the industry is now moving toward ultra-high Ni-content variants (Ni > 90%) to further enhance energy density and extend EV range. However, also in NCA, increasing Ni content, despite it is beneficial for energy density, accelerates capacity fade due to SEI growth and micro-crack formation at grain boundaries [224], [225]. To mitigate these issues, researchers are considering strategies like surface coatings and doping in order to maintain good mechanical stability and cycle life [226].

NMCA, still under research, incorporates small amounts of Mn and offers advantages over NCM and NCA in terms of improved mechanical and cycling stability, and reduced volume changes, even with similarly high levels of Ni content [227], [228]. As a result, high-Ni NCM, NCA and NMCA batteries are expected to secure a significant market share in the EV industry by the end of this decade [222]. For example, LG Chem is currently constructing a $3 billion battery cathode production facility in Tennessee, USA, dedicated to manufacturing NMCA cells [229]. Tesla and GM have announced to use these NMCA cells into their upcoming EV models. Instead, BMW and Toyota have planned to adopt ultra-high-Ni technology in 2025 and 2028, respectively [230], [231].

4.1.1.1.3. Lithium manganese oxide (LMO) – lithium manganese nickel oxide (LMNO). The electrochemical activity of spinel LMO was initially investigated in 1983 by Goodenough's research group at Oxford University [232], [233], while the first battery prototype was developed by Bellcore company in 1994 [234]. This ICM is promising for LIBs as Mn is less toxic than Co, is cheaper, and is available in greater abundance. The three-dimensional diffusion of Li^+ in the spinel crystal structure greatly improves the flow of current and reduces internal resistance, thereby resulting in fast charging and high-current discharge [223]. Another important positive aspect of LMO is its safety. Compared to layered oxides, LMO stores less energy at elevated temperatures, thereby reducing the risk of thermal runaway.

Despite these advantages, the specific capacity of LMO is limited to around (90–120) mAh/g, which results in lower specific and volumetric energy density than NCM and NCA ICMs. The material also shows capacity fade and reduced lifespan due to the dissolution of Mn-ions in the electrolyte at elevated temperatures. Such limitations restrict its use to small applications [104]. To overcome this issues and boost energy density, LMO is often blended with NCM. This combination has been used in different EVs such as the Nissan Leaf, BMW i3, and Chevrolet Bolt [223], [235], [236].

One more strategy for increasing the energy density of LMO is to partially replace Mn with Ni to form LMNO. While LMNO shares structural and chemical similarities with LMO [237], its composition (i.e., $LiMn_{1.5}Ni_{0.5}O_2$) sets it apart. Unlike LMO, LMNO utilizes the redox couple Ni^{2+}/Ni^{4+}, which operates at high voltage of 4.5–4.75 V (vs. Li/Li^+) [238]. It is important to note that only the Ni-based reaction is used, keeping Mn in a stable oxidation state. This is because the Mn^{3+}/Mn^{4+} redox pair is less stable and operates at a lower voltage [238].

Advantages that LMNO provides include high reversible operating voltage, Co-free composition, and moderate Ni content when compared with high-Ni NCM/NCA ICMs. In addition to this, it offers higher energy density and improved cycling stability over conventional LMO. However, like LMO, the major challenges faced by LMNO are Mn-ions dissolution, which leads to capacity fading [239], [240], [241], and interfacial reactions with the electrolyte at high voltage and temperature, which reduce cycle life [238], [239]. To enhance lifespan, electrolytes with oxidation stability above 5 V (vs. Li/Li^+) are required. Other means to mitigate degradation include reduction of particle size, optimization of morphology, doping, and surface modifications, all of which serve to minimize electrolyte decomposition and interfacial instability [238], [240].

4.1.1.2. Polyanion compounds. In exploring new cathode active materials, researchers have developed a new class polyanion-based ICMs, where large $(XO_4)_3^-$ groups (X = S, P, Si, As, Mo, W) enhance redox potential and structural stability [171].

4.1.1.2.1. Lithium iron phosphate (LFP) – lithium manganese iron phosphate (LMFP). LFP is one of the most popular examples of polyanion-based ICMs, recognized for its stable olivine crystal structure and high-temperature resistance [236], [242], both of which make it safer than layered oxides such as NCM and NCA [243]. One of the most important advantages of LFP is its lower cost, as it does not contain expensive materials like Ni and Co. Its olivine structure, however, also results in slow Li^+ diffusion and low ionic conductivity [243]. These limitations can be mitigated through techniques such as reducing particle size and applying conductive carbon coatings [223].

Compared to NCM and NCA ICMs, LFP ICMs operate at a lower voltage (3.2 – 3.5 V vs Li/Li^+) and offer moderate specific capacities (150 – 160 mAh/g), resulting in reduced energy densities [244]. Despite this, the trend towards cell-to-pack designs has increased LFP's appeal, as it offers a safer, more affordable option, particularly for smaller EVs.

LMFP presents multiple advantages over LFP due in large part to its higher operating voltage (around 3.6 – 4.1 V versus Li/Li^+), which results in improved specific and volumetric energy densities. In spite of this improved performance, LMFP remains cost-effective, requiring only Li as an expensive material, like LFP [245]. To increase operating voltage and therefore energy density, higher Mn content is preferred [246]. However, high Mn levels can slow Li^+ diffusion and reduce cycle life due to the dissolution of Mn-ions. As a result, Mn content should typically not exceed x = 0.8, with most commercial LMFPs containing around x = 0.6 [247].

A good example of a commercial LMFP cell is the "Astroinno L600" cell from the Chinese manufacturer Gotion, which achieves a specific energy of 240 Wh/kg, a volumetric energy density of 525 Wh/L, and a

cycle life of 4,000 cycles at room temperature [248].

4.1.2. Performance comparison

Fig. 14 uses spider charts to compare the main key performance parameters of commercial ICMs used in LIBs. Meanwhile, Table 4 provides a quantitative summary of these performance metrics across all chemistries, and it also highlights the potential future improvements that can be achieved in specific energy density [104], [109], [171], [191], [192], [193], [194], [195], [196], [197], [198], [248], [249].

By analysing both the spider charts of Fig. 14 and Table 4, it is evident that each ICM chemistry presents distinct strengths and limitations. For example, NCM and NCA offer high energy density but may be limited by thermal stability and cost, whereas LFP excels in safety and cycle life at the expense of lower energy density. LMFP provides a balanced compromise between these factors and emerges as a promising ICM for next-generation EVs. Consequently, this comparison highlights the trade-offs inherent to different cathode materials and can guide the selection of suitable chemistries depending on the specific performance priorities required. It is important to note that in Table 4, the symbols (↑) and (↓) indicate high and low values, respectively, for the corresponding performance indicators considered.

4.2. Anode active materials

Although anode materials do not participate to electrochemical reactions, they considerably influence the electrochemical characteristics of LIBs. For efficient operation, they must have a sufficiently porous structure with minimal defects. Additionally, they should include binders to preserve structural integrity, conductive additives to improve electronic transport, and an active material with high Li^+ conduction

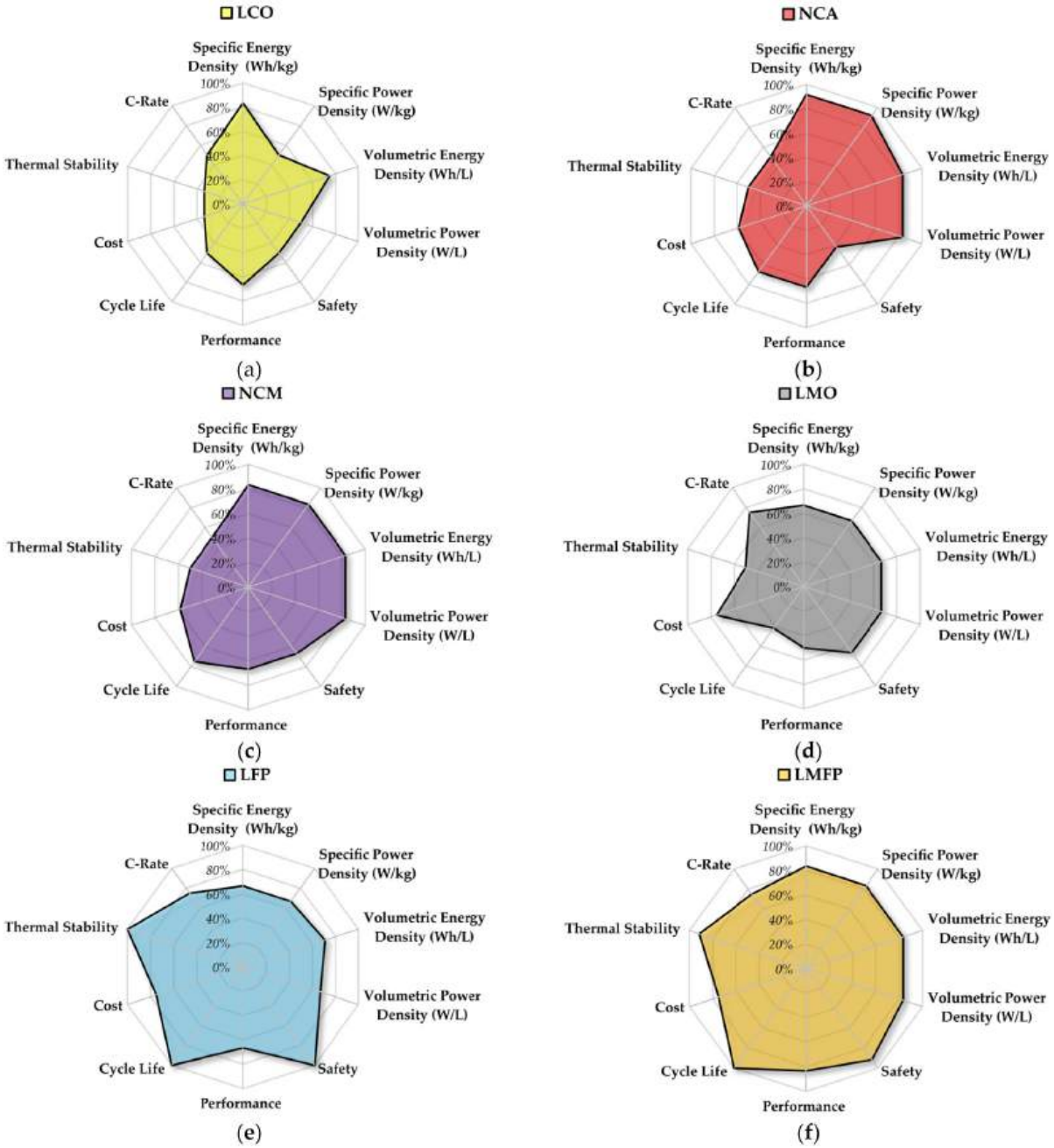

Fig. 14. Performance Comparison of different ICMS: (**a**) LCO; (**b**) NCM; (**c**) NCA; (**d**) LMO; (**e**) LFP; (**f**) LMFP.

Table 4
Specifications, advantages, disadvantages, and future energy potential of ICMs used in LIBs for EVs [104], [109], [171], [191], [192], [193], [194], [195], [196], [197], [198], [248], [249].

	LCO	NCM	NCA	LMO	LMNO	LFP	LMFP
Development Year	1991	2008	1999	1996	1999	1997	2015
Crystal Structure	Layered	Layered	Layered	Spinel	Spinel	Olivine	Olivine
Compound	$LiCoO_2$	$LiNi_{(1-x-y)}Co_xMn_yO_2$	$LiNi_{(1-x-y)}Co_xAl_yO_2$	$LiMn_2O_4$	$LiMn_{1.5}Ni_{0.5}O_2$	$LiFePO_4$	$LiMn_xFe_{1-x}PO_4$
Theoretical Specific Capacity (mAh/g)	274	275 – 280	275 – 280	149	146	170	170
Practical Specific Capacity (mAh/g)	120 – 160	150 – 210	140 – 230	90 – 120	115 – 125	150 – 160	135 – 160
Operating Voltage (V vs Li/Li^+)	4.2 – 3	4.2 – 3	4.2 – 3	4.4 – 3.2	4.8 – 3.5	3.65 – 2.5	4.4 – 2.5
Av. Operating Voltage (V vs Li/Li^+)	3.6 – 3.9	3.7 – 4.1	3.7 – 4	4 – 4.2	4.6 – 4.8	3.2 – 3.5	3.5 – 4.1
Discharge Curve Form	Slope	Slope	Slope	Flat	Flat	Flat	Flat
Commercial S. E. Density (Wh/kg)	150 – 240	220 – 240	250 – 300	100–150	–	90 – 160	110 – 240
Commercial V. E. Density (Wh/L)	≈ 400	≈ 500	≈ 550	≈ 350	–	≈ 385	≈ 525
Charging Rate (C)	1	0.7 – 1	0.7 – 1	0.7 – 1; 3	–	1	1
Discharging Rate (C)	1	1; 2	1	1; 10	–	1; 25	1; 25
Cycle Life	500 – 1000	1000 – 2000	1000	300 – 700	–	4000	4000
Material Cost (€/kg)	40 – 60	25 – 35	23 – 32	8 – 15	–	8 – 15	10 – 16
Thermal Runaway (°C)	150	210	150	250	–	270	270
Future S. E. Density (Wh/kg)	720	610 – 780	760	490	590	510	650
Pros	↑ S. E. Density	↑ E. Densities (↑ Ni) ↑ P. Densities (↑ Ni)	↑ E. Densities (↑ Ni) ↑ P. Densities (↑ Ni)	↑ S. P. Density	–	↑ Safety ↑ Thermal Stability ↑ Cycle Life ↓ Cost	↑ Safety ↑ Thermal Stability ↑ Cycle Life ↓ Cost
Cons	↑ Cost ↓ Cycle Life ↓ Safety	↑ Cost (↑ Ni/Co)	↓ Safety ↑ Cost (↑ Ni/Co)	↓ Cycle Life	–	↓ S. E. Density	–
Potential for next-generation EVs	No	Yes	Yes	Yes, with NCM	Yes	Yes	Yes
Market Share	Dumped	Dominant	Dominant	Small	Ready to go	Expanding	Expanding

capabilities.

The earliest anode material considered for LIBs was Li-metal. However, its short cycle life and safety problems, which are mainly due to dendrite formation during repeated charge/discharge cycles, hindered its commercialization and led researchers to search for other alternatives [250], [251], or to explore novel Li-metal stabilization strategies [252], [253]

Over the years, extensive research has resulted in the discovery of numerous anode materials. The latter can be generally classified into three types: intercalation anode materials (e.g., carbon-based [254], [255] and titanium-based [256], [257]), conversion anode materials (e.g., transition metal oxides [258]), and alloying anode materials (e.g., silicon-based compounds [259]).

Fig. 15a compares the specific capacity and average operating voltage of each anode active material groups [171], [260]. In turn, their charge and discharge curves are shown in Fig. 15b, highlighting the voltage hysteresis associated with the representative material of each group [171].

It is important to note that this review focuses solely on recent advancements in the most relevant intercalation anode materials (IAMs) and alloying anode materials (AAMs) used for EV applications. Specifically, it examines IAMs such as graphite (carbon-based) and lithium titanate oxide or LTO (titanium-based), while among AAMs, only Si is considered. Although conversion anode materials (CAMs), such as manganous oxide (MnO – a transition metal oxide), offer promising features, their high voltage hysteresis (up to 2 V), poor electronic and

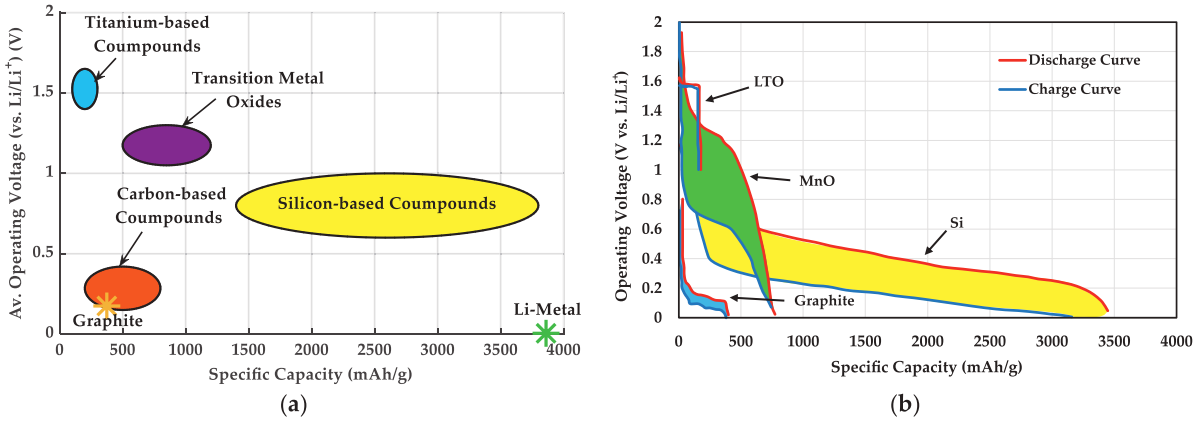

Fig. 15. Anode materials: (**a**) Approximate range of average discharge operating voltage ($LivsLi^+$), practical and specific capacity; (**b**) Charge–discharge profiles at low charge/discharge rates, showing voltage hysteresis, adapted from [171].

ionic conductivity, and continuous electrolyte decomposition limit their practical use [261]. As a result, they are not included in this discussion. For further details, see [261], [262].

4.2.1. Intercalation anode materials

Similar to ICMs, IAMs operate through the intercalation and deintercalation of Li^+ within the crystal lattice of the host material. LIBs that use ICMs as the cathode and IAMs as the anode are commonly referred to as rocking-chair batteries [263].

IAMs can be classified into two main groups based on their composition. These include carbon-based compounds and titanium-based compounds. In EV applications, graphite (C) is the most used carbon-based anode materials, while lithium titanate oxide ($Li_4Ti_5O_{12}$ or LTO) is the main titanium-based option.

4.2.1.1. Graphite (C). Graphite was the first commercialized LIB anode active material and remains one of the most used and well-known [264]. Nevertheless, this IAM and its production have not reached their final stage of development. In general, graphite can be obtained naturally by extracting it from mines (known as natural graphite, NG) or it can be produced through high-temperature processes using organic precursors like tar (referred to as synthetic graphite, SG) [104]. As a layered carbon material, Li^+ can be intercalated to form layered LiC_6. This process, which occurs at an operating discharge voltage below 0.2 V (vs. Li^+/Li), exhibits strong dynamic performance for Li^+ intercalation, including good mechanical stability, electrical conductivity, and Li^+ transport [265]. In addition to this, graphite presents low cost, wide availability, non-toxicity, low delithiation operating voltage (vs. Li^+/Li), high electrical conductivity, and relatively low volume change during lithiation/delithiation [266], [267]. Furthermore, thanks to its large grain structure, specific capacities that are close to the theoretical value can be obtained. All these characteristics make it an attractive anode material with a good balance of energy density, power density, and cycle life compared to other IAMs.

Despite these advantages, the low graphite theoretical capacity (around 372 mAh/g [171]) and slow charging capability limit its feasibility for high-power applications. The low lithiation operating voltage, similar to the voltage for Li-metal stripping, also leads to dendrite formation and SEI growth [268]. Moreover, since the compatibility of graphite with organic-based electrolytes is poor, the organic solvent intercalates together with the Li^+ between the graphitic planes (i.e. graphite exfoliation degradation mechanism), reducing cycle life and capacity storage [262].

To improve the electrochemical performance and lifetime of this IAM, two main methods are proposed. The first consists of accelerating Li^+ transport in the electrode by reducing particle size and adjusting the morphology of the material [269]. The second aims to improve the interfacial reaction of graphite with the electrolyte to grow a thinner, more stable SEI layer. This can be done by coating the graphite with a thin layer of amorphous carbon, which improves cycle life and thermal behaviour [270].

Alternatively, emerging approaches such as anode-free lithium metal batteries have been proposed to overcome the intrinsic limitations of graphite, offering higher energy densities and improved cycling stability [271]

4.2.1.2. Lithium titanate oxide (LTO). Another important IAM is spinel LTO, which is well-known for its high thermal stability and good rate capability [272], [273]. One of its key advantages is the "zero-strain" mechanism, which means that the volume change during Li^+ intercalation and deintercalation is very small (around 0.2%) [274], [275]. This also leads to low voltage hysteresis in the charge–discharge process. Additionally, its high operating voltage (around 1.55 V vs. Li/Li^+) prevents dendrite formation and SEI growth which in turn improves electrochemical performance, enhances stability, and leads to a long cycle life [171]. Despite its very low theoretical capacities (around 175 mAh/g and 610 mAh/cm^3 [171]) and high cost of Ti, these exceptional characteristics make LTO highly suitable for EV applications.

4.2.2. Alloying anode materials

Although graphite represents the state of the art of anode active material for commercial LIBs due to its abundance, low cost, and structural stability, its limited theoretical capacity (around 372 mAh/g) and safety concerns restrict its suitability for applications that demand increasingly higher energy and power density, such as EVs [276], [277], [278].

To overcome these limitations, AAMs, which can provide a specific capacity that is two to ten times higher than that of carbon-based anodes, are employed [260]. Alloying materials refer to elements such as Si, Ge, Sn, Pb, As, Sb and Bi that electrochemically alloy and form compound phases with Li at low potential (below 1 V) [261], [262]. More specifically, here, Li^+ reacts with the element (M) to form a compound of the type Li_nM, where n is a number greater than one [279].

Among the various researched AAMs, the excellent characteristics of Si make it the most viable option for high-performance LIBs, particularly for those applications which require high energy density like EVs. A major focus of this review is therefore on silicon-based compounds.

4.2.2.1. Silicon-based compounds. Of all AAMs, Si has the highest theoretical capacity (around 3579 mAh/g [171]). It presents also other important features such as a relatively low delithiation potential, abundance, low cost, chemical stability, and non-toxicity [280], [281]. However, despite these advantages, Si suffers from abnormal volume change during lithiation, which can cause electrode particles to crack and lose electrical contact from the current collector [265]. In addition, this volume expansion damages the SEI protective layer cycle after cycle, leading to continuous electrolyte decomposition and Li loss [282], [283]. As a result, silicon-based anodes typically have a limited cycle life.

A successful strategy to overcome this limitation is to use Si as an additive in graphite to form Si/C composite anode [282], [284]. Two important aspects must be highlighted. First, the Si particles must be sufficiently small (less than 150 nm) to improve mechanical stability [285]. Second, these active particles should be encapsulated in a carbon shell with sufficient void space to allow for volume expansion in order to stabilize the SEI layer and prolong cycle life [286], [287]. Electrolyte additives and binders can further enhance SEI stability and extend cycle life [288], [289].

4.2.3. Performance comparison

Fig. 16 uses spider charts to compare the main key performance parameters of commercial anode active materials used in LIBs. Meanwhile, Table 5 provides a quantitative summary of these performance metrics for all the anode active materials examined [104], [109], [171], [260], [262].

By analysing both the spider charts in Fig. 16 and the quantitative data in Table 5, several trends can be observed. Graphite offers moderate characteristics which make it the most used IAMs. Li-metal provides the highest energy density, although suffers from safety issues such as dendrite formation and TR. LTO is extremely safe and thermally stable, with outstanding cycle life, but its low specific capacity limits overall energy density. Si and Si/C composites present a balanced trade-off: pure Si offers very high capacity (and thus, energy density) but poor cycle stability and significant volume expansion, while Si/C composites mitigate these issues and achieve good energy density with improved cycle life and safety.

Overall, Si/C emerges as the most promising IAMs for next-generation EVs, combining strong performance in both energy density and safety. It is important to note that in Table 5, the symbols (↑) and (↓) indicate high and low values, respectively, for the corresponding

Fig. 16. Performance Comparison of different anode active materials: (**a**) Li-Metal; (**b**) Graphite; (**c**) LTO; (**d**) Si; (**e**) Si/C.

performance indicators.

4.3. Cathode and anode combinations

As mentioned earlier, the electrochemical performance of a LIB depends on the combination of cathode and anode active materials, which profoundly influences key performance parameters such as energy density, power density, thermal stability and safety. Fig. 17a illustrates the operating voltage ranges for commonly used cathode–anode combinations, where the reported cell voltage corresponds to the open–circuit condition. Among the various combinations previously examined, a LIB cell utilizing NCM as ICM and graphite as IAM (a configuration widely used in EVs) achieves a relatively high OCV of 3.7 V, maximizing both energy and power density. In contrast, a LIB cell that uses LFP as ICM and an LTO as IAM operates at a OCV of only 1.9 V, which is even lower than that of Pb–acid batteries. As previously discussed, higher-voltage LIB cells can enhance energy and power output, whereas lower-voltage configurations generally offer improved safety and thermal stability.

Fig. 17b shows the operating voltage of the anode, cathode, and full cell across the 0–100% SoC range for a Panasonic 18650 cell (with an NCA cathode and graphite anode) [290]. During discharge, Li^+ are extracted from the anode and intercalated into the cathode. Because of this, the anode operating voltage increases while the cathode operating voltage decreases. By observing the graph, it is evident that the anode is fully utilized. At 100% SoC, the anode is almost completely lithiated, thus, its operating voltage (vs. Li/Li^+) is very close to zero. Conversely, at 0% SoC, the anode is completely delithiated, which causes the operating voltage (vs. Li/Li^+) to rise significantly.

Tables 6 and 7 summarize the LIBs used in commercial EVs, focusing respectively on medium and low Co-content chemistries. Each table presents the cell chemistry, defined by the specific combination of anode

Table 5
Specifications, advantages and disadvantages of anode active materials used in LIBs for EVs [104], [109], [171], [260], [262].

	Li-Metal	Graphite	LTO	Si	Si/C
Type of anode	AAM	IAM	IAM	AAM	AAM
Theoretical Specific Capacity (mAh/g)	3860	372	175	3579	> 372
Density (g/ cm^3)	0.534	2.26	3.48	2.33	1.5 – 2
Theoretical Volumetric Capacity (mAh/cm^3)	2061	841	610	8339	> 841
Av. operating voltage (V vs Li/Li^+)	0	0.1	1.55	0.22	0.1 – 0.22
Volume expansion (%)	> 30	10	0.2	270	≈ 20
Specific energy density (Wh/kg)	> 300	< 280	≈ 70	> 300	≈ 300
Volumetric energy density (Wh/L)	1000	< 750	≈ 150	> 900	≈ 800
Material Cost (€/kg)	80 – 200	5 – 9	> 20	> 30	> 10
Pros	↑ E. Densities ↑ P. Densities	↑ Performance	↑ Th. Stability ↑ C-rate ↑ Cycle Life ↑ Safety	↑ E. Densities ↑ P. Densities	↑ Performance
Cons	↓ Cycle Life ↓ Safety ↑ Cost	↓ C-rate ↓ Cost	↓ S. E. Density	↓ Cycle Life ↓ Safety ↑ Cost	–
Potential for next-generation EVs	Yes	Yes	Yes	Yes	Yes

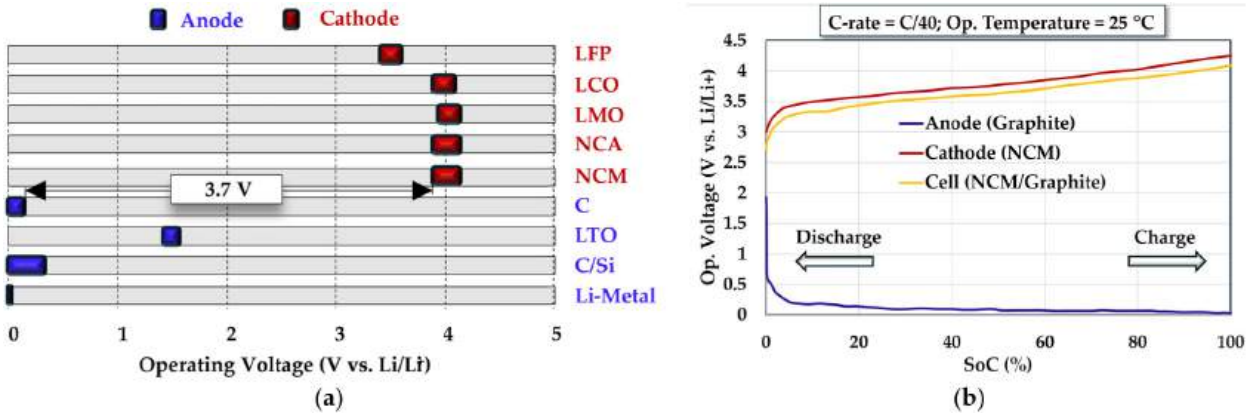

Fig. 17. (**a**) Operating voltage ranges (vs. Li/Li^+) for commonly used cathode–anode combinations; (**b**) Operating voltage (vs. Li/Li^+) of NCA anode, graphite cathode and full cell (Panasonic 18650), adapted from [290]

Table 6
Specifications of various LIB types used in commercial EVs (with medium Co-content) [291], [292], [293], [294], [295], [296].

Anode	Cathode	Nominal Voltage (V)	Capacity (Ah)	Charge Rate (C)	Discharge Rate (C)	Sp. Energy Density (Wh/kg)	Vol. Energy Density (Wh/L)	Life Cycle	Thermal Runway (° C)	Manufacturers	EV model	Battery Energy (kWh)	Driving Range (km)
C	NCM	3.65 – 4	25	0.7 – 1	1	130 – 241	215	1000 – 2000	210	Panasonic/ Sanyo	VW e-Golf (2015)	24	135 – 190
			56				393			LG Chem	Chevrolet Bolt (2016)	60	383
			59				466				Renault Zoe 50 (2017)	52	390
	NCA	3.6 – 3.65	3.2	0.7	1	200 – 310	673	500	150	Panasonic, SAFT, LG Chem	Tesla S (2012)	≈ 100	595
Si			3.4								Tesla X (2015)		525
Si/C			4.75				683				Tesla 3 (2017)	≈ 75	500
											Tesla Y (2020)	75 – 100	480 – 595
LTO	NCM NCA	2.3 2.3 – 2.5	20	1	10	89 70 – 85	200	3000 – 7000	–	Toshiba	Honda Fit EV (2013)	20	130

Table 7
Specifications of various LIB types used in commercial EVs (with low Co-content) [291], [292], [293], [294].

Anode	Cathode	Nominal Voltage (V)	Capacity (Ah)	Charge Rate (C)	Discharge Rate (C)	Sp. Energy Density (Wh/kg)	Vol. Energy Density (Wh/L)	Life Cycle	Thermal Runway (° C)	Manufacturers	EV model	Battery Energy (kWh)	Driving Range (km)
C	LMO-NCM	3.7	50	0.7 – 1	1	109	218	300 – 700	250	Li Energy Japan	Mitsubishi i-MIEV (2008)	16	100 – 160
		3.65	63			172	312			Samsung SDI	Fiat 500e (2013)	24	140
	LMO-NCA-NCM	3.7	37			185	357				VW e-Golf SEL (2016)	≈ 36	201
			94			189					BMW i3 (2017)	33 – 43	183 – 246
	LMO-NCA	3.75	33			155	309			AESC	Nissan Leaf (2015)	30	172
			40			167	3.75				Nissan Leaf S Plus	62	364
	LFP	3.2 – 3.3	27	1	1	90 – 130	144	1000 – 2000	270	A123, Valence Tech, BYD	Chevrolet Spark	19	132
			–				–				BAIC EC220		206
		3.2	–			140 – 166	279			BYD	BYD Tang Elect.	86	505

and cathode active materials, along with key performance parameters such as capacity, charge and discharge rate, specific and volumetric energy density, cycle life, and thermal runaway onset temperature. In addition, these two tables include information on the battery manufacturers, the corresponding EV models, their driving range (km), and the total battery energy capacity (kWh) [291], [292], [293], [294], [295], [296].

Note that in Tables 6 and 7, cycle life values are indicative and strongly depend on operating conditions. Reported ranges for NCM and NCA (up to 3000 – 7000 cycles) correspond to optimized conditions, such as partial DoD, moderate C-rates, and controlled temperature. Under full DoD, typical lifespans are significantly lower (1000 – 3000 cycles). Furthermore, LFP chemistries provide a very good driving range (over 500 km per charge for kWh – BYD EV) while ensuring thermal runaway safety and maintaining good cycle life.

5. LIB safety

As previously discussed, materials commonly used in EVs for their high energy density, such as NCM and NCA, often show lower thermal stability, which can result in serious safety issues like thermal runaway (TR) [297]. During normal operation, under abuse conditions or during an EV accident, TR can lead the battery to release smoke, ignite, or even explode [298]. These risks increase public concern about battery safety and still represent a great barrier to the large-scale adoption of EVs.

During normal battery operation, the continuous movement of Li^+ between the anode and the cathode generates substantial heat, which may become problematic if not properly dissipated, especially on hot days or in a large battery pack [299]. In this context, the Battery Management System (BMS), which is an electronic control unit mounted on each LIB, plays a crucial role [300], [301]. In particular, the BMS is responsible for monitoring vital parameters of each cell, such as operating voltage, current, and temperature. As a result, it enables effective control of both the cooling and venting systems, which in turn helps to prevent those conditions that may trigger TR and ensure safe battery operation [302], [303], [304]. However, under abuse conditions, the chance of TR increases greatly, despite the proper functioning of the BMS.

Abuse conditions, which include mechanical abuse (e.g., battery crush, vibration, collision or penetration), electrical abuse (e.g., battery overcharge, overdischarge or short circuit) and thermal abuse (e.g., battery overheating) can trigger a chain of dangerous exothermic side reactions in one or more cells of a battery pack [305], [306]. This process, known as the Heat-Temperature-Reaction (HTR) loop, involves electrodes, electrode/electrolyte interface, electrolyte, and separator [307]. Once TR begins in a single cell, the event can propagate to adjacent cells, resulting in catastrophic battery failure (see Fig. 18a) [308], [309].

In general, TR occurs when the HTR loop causes heat generation to exceed the heat dissipation capacity of the battery [310]. Fig. 18b illustrates the chain reaction mechanism that leads to TR in a LIB cell. The process starts with the decomposition of the SEI, followed by exothermic reactions between the anode and the electrolyte [72], [306]. As the temperature rises, flammable hydrocarbon gases are generated from reactions between Li^+ and the electrolyte solvents, causing a rapid increase in internal pressure [311]. Since the rate of heat generation surpasses the rate of heat dissipation, the continued temperature increase leads to the melting of separators. This, in turn, causes direct contact between the positive and negative electrodes, leading to an internal short circuit and cell smoke. At this stage, TR becomes inevitable. The temperature continues to rise, and the cathode active material starts to decompose and release additional oxygen. This, in turn, leads to battery combustion and fire [310].

Fig. 18c illustrates the four stages of battery failure, highlighting two regions. The preventative zone, where timely action by the BMS can effectively stop the onset of TR, and the containment zone, where TR and battery failure become unavoidable.

Fig. 18d offers a comprehensive overview of TR in LIB, mapping the path from its root causes, such as EV accidents, cell defects or malfunctioning of the BMS, to its severe outcomes like battery smoke, fire or explosion [53].

The following subsections will illustrate briefly how each type of abuse condition can impact LIB safety.

5.1. Mechanical abuse

Penetration, compression, and deformation of the cell during EV accidents can tear the separator, allowing the electrodes to come into direct contact. The resulting short circuit can trigger TR and lead to catastrophic battery failure [312]. In such cases, the BMS is unable to intervene in order to avoid the event. However, it is important to note that the layout and structural design of the battery pack within the

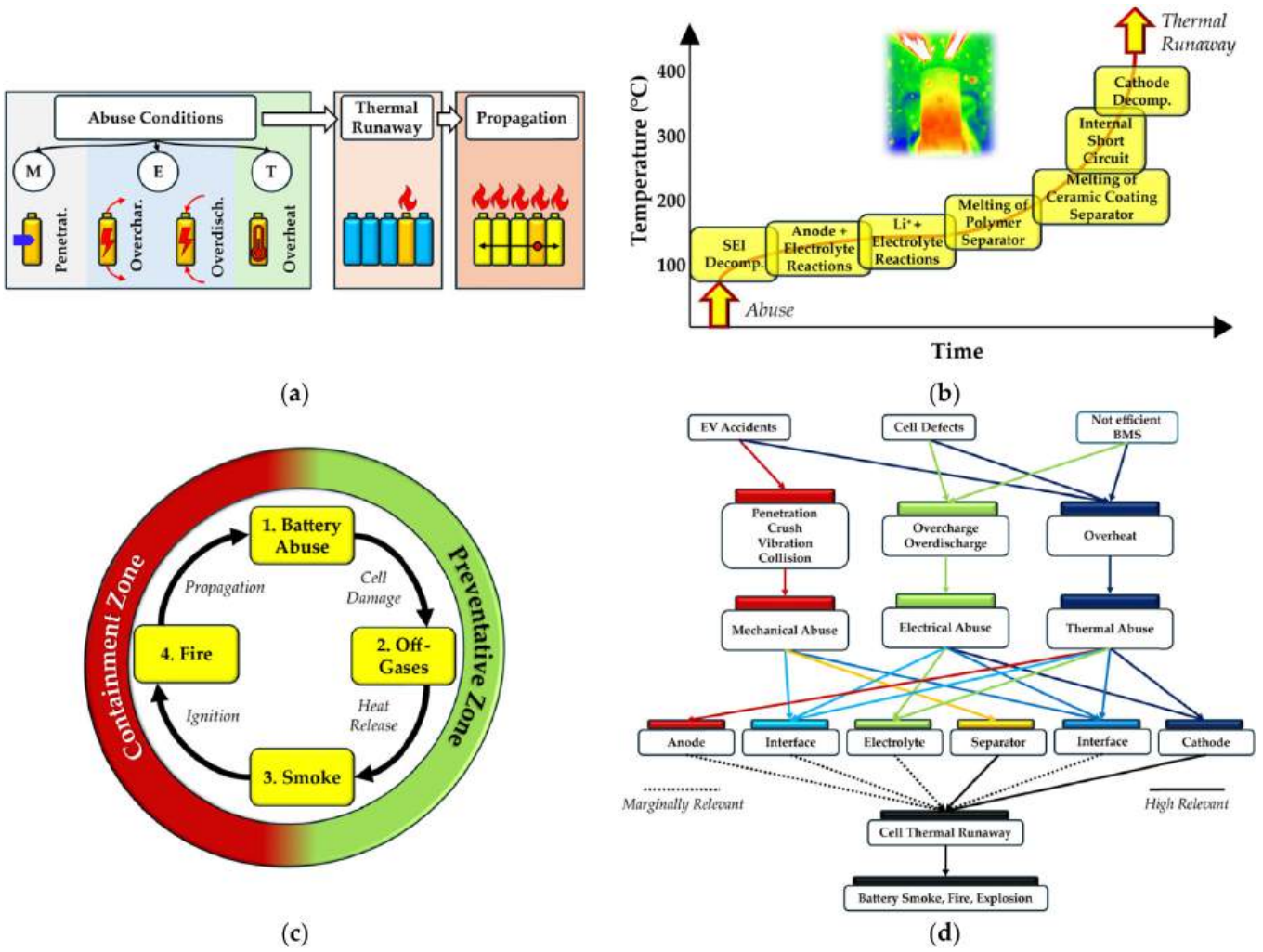

Fig. 18. (**a**) Abuse conditions, cell TR and propagation; (**b**) Chain reaction mechanisms during TR; (**c**) preventive and containment zone; (**d**) TR map: from root causes to severe outcomes, adapted from [53], [72].

vehicle significantly influence its response during a crash [313].

5.2. Electrical abuse

Battery cell overcharge can happen when the voltage of a single cell is not accurately monitored by the BMS [314]. In general, small deviations in voltage monitoring can cause slight overcharging. A minor overcharge typically results in capacity degradation. On the other hand, a very high SoC ($1.4 < SoC < 1.6$) can trigger harmful side reactions, which include Li^+ dendrite formation and cathode decomposition, which in turn can lead to TR and battery explosion [315], [316].

The principle of overdischarge is similar to that of overcharge. An overdischarge state occurs if a cell is forced to continue discharging. At very high DoD, critical side reactions such as SEI layer degradation and Cu current collector dissolution can trigger internal short circuits and TR [317], [318].

5.3. Thermal abuse

Localized high-temperature areas within a battery can be very problematic. Poor design of LIBs can cause high impedance at the metal contacts [319], [320]. When high current flows through the current collectors, it generates intense heat, leading to local overheating and potentially triggering TR [321].

To summarize, TR remains one of the most critical safety concerns in LIBs, limiting the widespread adoption of EVs due to the fear of accidents. To mitigate this risk, many countries now require LIBs to pass stringent safety standards, such as UN 38.3, UN R100, SAE J2464, IEC 62133, and GB/T 31485, before they can be approved for use in EV applications [314], [322]. Once the battery meets these standards, the risk of smoke, fire and explosion due to mechanical, electrical and thermal abuse conditions can be significantly reduced.

6. LIB recycling

6.1. Recycling processes

The production of LIBs depends on critical raw materials, many of which come from only a few countries. Around 70% of the Co supply is mined in the Democratic Republic of Congo, while China and Mozambique together produce about 70% of global graphite [323], [324]. This strong dependence on a limited number of sources highlights that effective recycling processes are essential at the LIBs EoL.

Battery recycling in Europe is primarily driven by the new European Batteries Regulation (EU 2023/1542), which came into effect in August 2023 [325]. At LIBs EoL, recycling involves the recovery of valuable components and materials from used batteries. Spent LIBs contain considerable amounts of high-value elements such as Co, Li, Mn and Ni, often in higher concentrations than those found in natural ores [326].

Compared to the primary extraction of raw materials, the use of

recycled materials can substantially reduce local environmental impacts, including energy consumption, earth and rock displacement, and water usage [327]. These benefits are especially evident when recycling processes are highly efficient, and the battery design is optimized for recyclability. As a consequence, manufacturers of LIBs are investing considerable efforts in the development and implementation of advanced recycling technologies. By 2030, the global recycling volume from EoL LIBs is projected to reach approximately 1.6 megatons [104].

Concerning the recycling processes, they are generally categorized into three well-established groups: pyrometallurgical, hydrometallurgical, and mechanical recycling [328], [329], [330]. These approaches are often combined to enhance the recovery efficiency in terms of both material quantity and purity. The goal is to achieve recycling rates of 80% for Li and 95% for Co, and Ni by the end of 2031 [104]. In line with these targets, LIBs for next-generation EVs are expected to contain at least 16% recycled Co, 6% recycled Li, and 6% recycled Ni [104].

Besides the above mentioned three groups, the concept of solvometallurgy has recently emerged as a new approach for the extraction of metals (including Li and Co) from ores, industrial process residues and batteries [331], [332]. The process involves non-aqueous solutions, where the term “non-aqueous” does not imply “anhydrous”, but rather “low water content” [331]. The basic operations are the following: solvent leaching; separation of the residue; purification of the leach solution by non-aqueous solvent extraction or non-aqueous ion exchange; and metal recovery by precipitation or electrolysis in non-aqueous electrolytes [331]. Solvometallurgy is similar to hydrometallurgy in that both the branches of extractive metallurgy use low-temperature processes, but with solvometallurgy there is no discrete water phase [332]. Both branches use organic or inorganic solvents, but solvometallurgy proves to be sustainable because it exploits green solvents, which means that all toxic or environmentally harmful solvents are avoided [331], [332].

6.2. Reuse, repurposing, and remanufacturing

Beyond recycling, strategies such as reuse, repurposing, and remanufacturing are increasingly considered for a more sustainable LIB lifetime [333], [334]. Reuse involves employing a EoL LIB from an EV in a secondary mobile application with lower performance demands. Repurposing refers to the use of spent batteries in energy storage systems. Remanufacturing focuses on restoring spent batteries and extend their functional lifetime. These second-life applications offer both economic and environmental advantages [335], [336]. However, the widespread adoption of second-life applications is still hindered by several challenges, which include uncertainties related to battery health and diagnostics, and a lack of standardized protocols for sharing battery design and status information [336].

The combination of recycling and second life strategies (reuse, remanufacturing, and repurpose) create the circular economy of batteries illustrated in fig. 19. This model highlights responsible material utilization through prolonged usage, waste minimized, material recovery or strategies that benefit both the society and the environment [337].

7. Beyond LIBs: Next-generation storage systems for EVs

The significant challenges that remain in Li-ion technology for a sustainable mobility have also driven the exploration of alternative battery chemistries. These next-generation 'beyond LIB' systems, including solid-state batteries (SSBs) and sodium-ion batteries (SIBs or Na-ions), as well as emerging technologies such as lithium-sulfur batteries (LSBs) and metal-air batteries (MABs), offer promising routes toward higher energy density, improved safety, and more environmentally friendly material usage.

7.1. SSBs

While conventional LIBs rely on liquid electrolytes and a porous separator to enable ion transport and prevent electrical short circuits, SSBs use solid electrolytes that simultaneously conduct ions and separate the electrodes [338]. This structural difference offers several advantages, including higher energy density, longer cycle life, enhanced safety, and a reduced environmental footprint compared to conventional LIBs. Additionally, under certain conditions, SSBs can support faster charging, making them particularly promising for next-generation EVs [339].

The electrodes used in SSBs are often similar to those in conventional LIBs. Typical anodes include Li-metal, graphite (C), or lithium-alloy

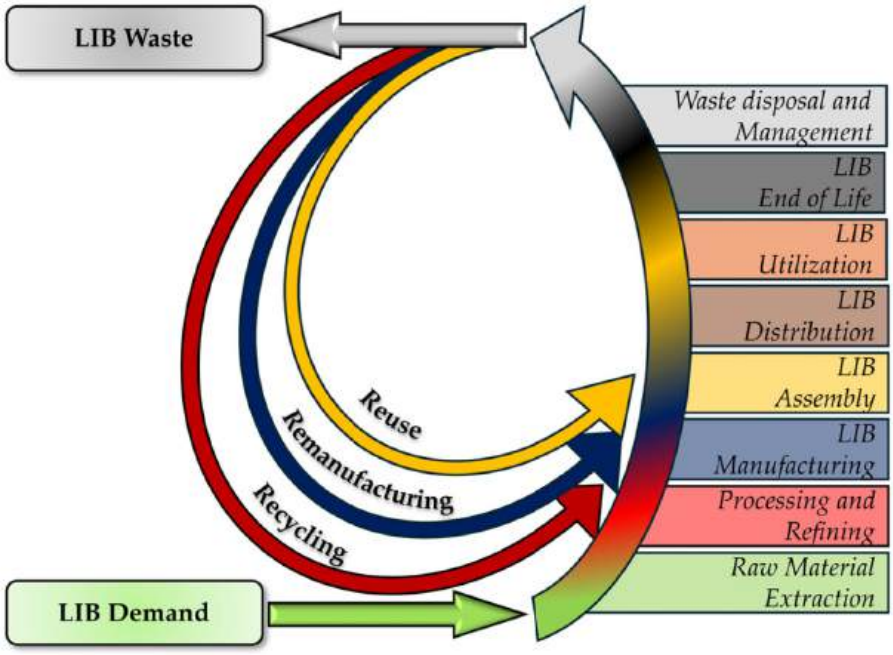

Fig. 19. The concept of circular economy for LIBs.

materials, while cathodes consist of layered oxides, polyanion compounds, or sulfur-based materials, all optimized for compatibility with solid electrolytes [340]. Among these, Li-metal anodes are especially attractive due to their potential to significantly boost energy density [341]. However, they face critical challenges, including dendrite formation during cycling, which can lead to internal short circuits, capacity fading, and safety hazards [342]. Moreover, Li-metal anodes often exhibit low CE, which limits performance over repeated charge–discharge cycles [343].

On the cathode side, advanced materials such as Li-rich NCM (LMNC) offer high discharge capacities (i.e., 200, 250, and 290 mAh/g at C, C/4, and C/20 rates, respectively) and can enable next-generation SSBs with volumetric energy densities up to 1000 Wh/L and specific energies around 400 Wh/kg [344]. These advances underscore the potential of SSBs to satisfy the stringent requirements projected for EV applications by 2030. Looking ahead, as investments and collaborations accelerate, the transition from laboratory-scale research to scalable manufacturing will be crucial to ensure the widespread adoption of SSB technology in real-world mobility systems.

7.2. SIBs

SIBs are emerging as a potential alternative to LIBs. Their basic charge and discharge mechanism is illustrated in Fig. 20b. Sodium (Na) shares many electrochemical properties with lithium (Li), and its abundance in the Earth's crust offers a clear cost advantage. Moreover, SIBs can use aluminium (Al) as the current collector for both electrodes, since Na does not alloy with Al. This eliminates the need for more expensive copper (Cu) on the anode, as in LIBs, reducing overall production costs [345].

Common negative-electrode materials for SIBs include hard carbon, sodium titanates, and alloying/conversion-type materials [345]. Hard carbon remains the most widely used, providing reversible specific capacities of approximately 700 mAh/g and good cycle stability [346]. Sodium titanates offer excellent structural stability and low insertion potentials but are limited by slower Na^+ (sodium ions) diffusion, which affects high-rate performance [347]. Alloying and conversion materials, such as tin or antimony-based compounds, can achieve high specific theoretical capacities but face challenges due to large volume changes and SEI instability [348]

SIBs can use either liquid or solid electrolytes. In liquid-electrolyte cells, a porous separator enables Na^+ (sodium ions) transport while

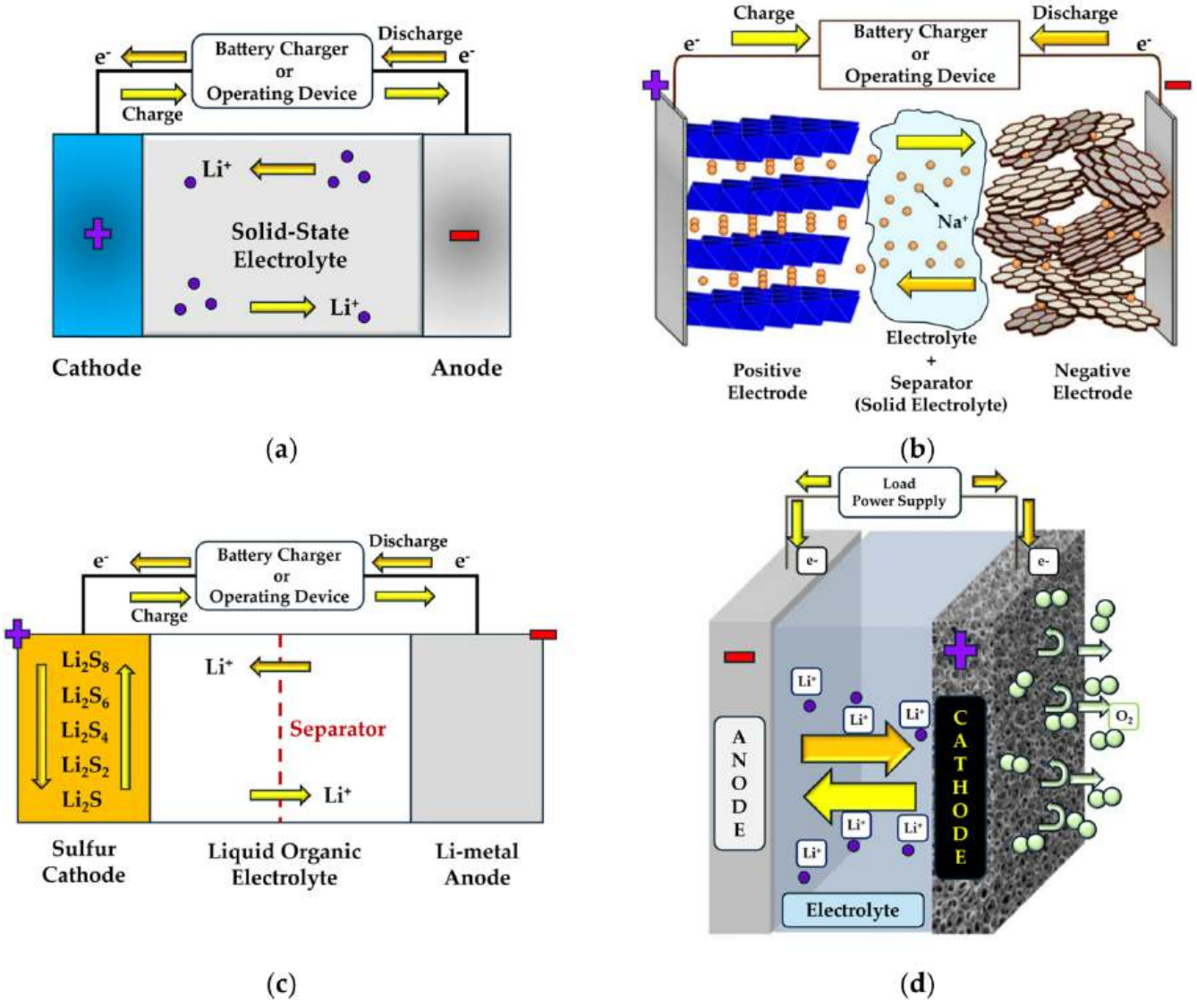

Fig. 20. Basic charge and discharge mechanism of emerging battery technologies: (**a**) SSBs; (**b**) SIBs; (**c**) LSBs; (**d**) non-aqueous LABs.

preventing short circuits, whereas solid electrolytes combine ion conduction and separation in a single layer, eliminating the need for a separate separator [345].

Positive-electrode materials primarily include layered transition metal oxides and polyanionic compounds [345]. Layered oxides deliver high capacity but are prone to phase-change degradation [348], while polyanionic and organic electrodes excel in stability and rate performance, with lower energy density [349], [350], [351], [352].

Despite these promising chemistries, SIBs currently deliver lower energy density (100–160 Wh/kg) compared to LIBs (>250 Wh/kg), which limits their suitability for EVs where high energy density and extended driving range are critical [353]. Consequently, SIBs are presently considered more appropriate for stationary energy storage or niche mobility applications, such as low-cost city cars and two-wheelers, where cost, safety, and sustainability are prioritized over long range [354]. Nevertheless, ongoing research into advanced electrode materials and optimized solid electrolytes may help close the performance gap, in order to enable the adoption of SIB technology in EVs in the next future.

7.3. LSBs

Among the emerging technologies for automotive batteries, LSBs stand out for their high theoretical capacity (1675 mAh/g), high energy density (~500 Wh/kg), low cost, and improved environmental performance [355], [356], [357]. Compared to SIBs with lower energy density and SSBs with higher cost, LSBs are considered a highly promising option for next-generation EVs. Several initiatives support their development, such as the EU's Advanced Lithium–Sulfur Battery Research (ALISE) Program and LG New Energy's plans for large-scale production [358].

A typical LSB consists of a Li metal anode, a sulfur cathode, an organic electrolyte, a separator, and metallic current collectors. Specifically, aluminium (Al) is generally used on the cathode side, while nickel (Ni) or copper (Cu) can serve as the current collector for the anode [359]. Unlike LIBs, which rely on intercalation, LSBs operate through a conversion mechanism involving the cleavage and reformation of S–S bonds in S_8. During discharge, sulfur is sequentially reduced to higher-order polysulfides (Li_2S_8, Li_2S_6, etc.), then to lower-order species, and finally to solid Li_2S (Fig. 20c). This multi-step, multi-electron process enables high capacity but also causes the "shuttle effect" of soluble polysulfides and Li dendrites, leading to capacity fading, limited cycle life and severe safety problems [360], [361].

To address these challenges, extensive research is devoted to cathode hosts, binders, interlayers, and advanced electrolytes. A particularly promising direction is the integration of sulfur chemistry with an all-solid-state architecture. In this configuration, the all-solid-state lithium–sulfur battery (A-LSB) mitigates polysulfide shuttling and safety risks while delivering enhanced performance [358]. This combination is regarded as an ideal next-generation power battery for EV applications, offering both high efficiency and improved environmental sustainability.

7.4. MABs

Currently, known metal–air batteries (MABs) are based on metals such as Li, Na, Zn, Mg, Al, and Fe [362]. Among these, lithium–air batteries (LABs) stand out as one of the most promising technologies, attracting considerable attention due to their exceptional theoretical capacity (3862 mAh/g) and high energy density, which can reach ~1000 Wh/kg, far surpassing conventional LIBs and approaching the energy density of gasoline [363]. These characteristics make LABs a highly attractive option for next-generation EVs, with the potential to drastically extend driving range while maintaining low weight.

The working principle (Fig. 20d) relies on a Li-metal anode and a porous air cathode, where oxygen (O_2) from the atmosphere serves as the active material. During discharge, Li^+ react with O_2 to form lithium oxides or peroxides (mainly Li_2O_2), which can be electrochemically decomposed back into Li and O_2 upon charging [364], [365]. Depending on the electrolyte, four main configurations have been proposed: non-aqueous, aqueous, hybrid, and all-solid-state LABs, each exhibiting different reaction pathways and associated challenges [366], [367].

Despite their promise, practical deployment is hindered by cathode clogging due to Li_2O_2 precipitation in the porous carbon structure, limited cycle life, lithium dendrite formation, and parasitic reactions with CO_2 from ambient air. Ongoing research focuses on more stable electrolytes, protective membranes, and solid-state designs to improve reversibility and durability. If these challenges are addressed, LABs could become a disruptive technology for automotive applications, enabling EVs with ranges comparable to conventional ICEVs.

7.5. Performance comparison

Fig. 21 uses spider charts to compare the main key performance parameters of different battery technologies. By analysing the spider charts in Fig. 21, it is clear that each technology exhibits distinct strengths and trade-offs.

LABs and LSBs are characterized by very high specific energy densities, suggesting the potential to significantly extend EV driving range. SSBs and LIBs offer a balanced combination of safety, cycle life, and thermal stability. SIBs provide cost and sustainability benefits due to the abundance of sodium. LSBs and LABs face challenges such as dendrite formation, polysulfide shuttling, or oxygen reactivity, which impact cycle life and safety. Overall, these differences illustrate how specific technologies may be better suited to particular applications in next-generation EVs, depending on the targeted performance priorities.

8. Discussion and future perspectives

LIBs remain the dominant battery technology for EVs due to their high energy density, long cycle life, and relatively mature industrialization. However, as this review has shown, they still face critical limitations that hinder their widespread deployment compared to ICEVs. These include limited driving range, long charging times, high costs, and safety concerns, all of which are closely linked to battery chemistry and design.

Electrode materials are at the heart of LIB performance. Commercial cathodes such as NCM, NCA, and LFP currently offer the best balance between energy density, cycle life, and safety, while ongoing research is directed toward Ni-rich and Li-rich formulations to further increase capacity. On the anode side, graphite remains the commercial standard, although silicon composites and, ultimately, Li-metal anodes promise to dramatically enhance specific capacity. Nevertheless, these emerging solutions suffer from significant challenges such as large volumetric expansion, poor conductivity, and unstable interfacial chemistry, which complicate their industrial implementation.

Degradation mechanisms play a decisive role in both performance and safety. On the cathode side, particle cracking, structural disorder, and transition-metal dissolution reduce cyclability. At the anode, SEI growth, Li plating, and dendritic formations are key contributors to capacity fade and internal resistance increase. In particular, Li dendrites represent a severe safety risk, as they can pierce the separator, trigger short circuits, and potentially initiate TR. These degradation processes ultimately lead to the loss of cyclable Li, reduced electrode activity, and higher impedance, shortening the battery's useful life.

Performance metrics of LIBs are already very high, with specific energy values between 200 – 300 Wh/kg. However, their sensitivity to operating conditions remains problematic. Both low- and high-temperature environments accelerate degradation and compromise safety, underlining the importance of robust BMS. Similarly, fast charging at high C-rates generates excessive heat and mechanical stress, shortening cycle life.

Safety remains the most critical concern. TR, electrolyte

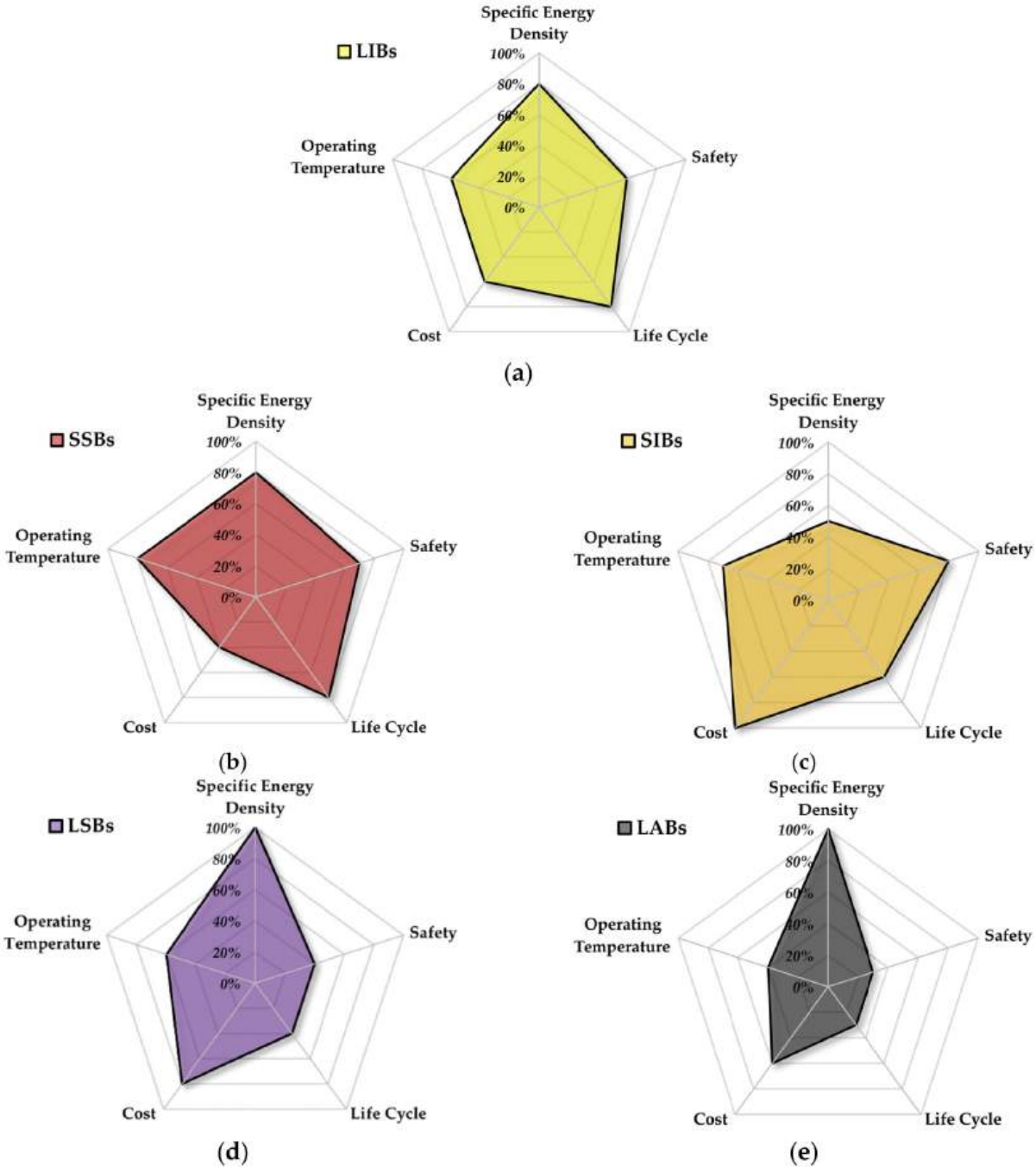

Fig. 21. Performance Comparison of different battery technologies: (**a**) LIBs; (**b**) SSBs; (**c**) SIBs; (**d**) LSBs; (**e**) LABs.

flammability, and structural instabilities have been at the center of several well-documented incidents. Advances in material design (non-flammable electrolytes, solid-state separators), BMS, and protective architectures can mitigate risks but have not eliminated them completely. Ensuring safety under mechanical, electrical, and thermal abuse conditions is thus a top priority for next-generation EV batteries.

Recycling and EoL strategies are becoming increasingly important as EV adoption accelerates. Pyrometallurgical and hydrometallurgical processes are currently the main methods for recovering valuable metals such as Li, Ni, Co, and Mn, but they remain energy-intensive. Emerging direct recycling approaches, which aim to regenerate cathode materials without breaking down their crystal structure, are promising for reducing costs and environmental impact. At the same time, second-life applications (such as repurposing EV batteries with reduced capacity for stationary storage) can extend the functional lifespan of LIBs before final recycling. Efficient EoL management will be essential to reduce dependence on critical raw materials and to meet future sustainability targets.

Despite progress, critical barriers remain. Battery costs are still high, autonomy is often lower than consumer expectations, charging times remain long, and reliance on scarce materials such as Co and Ni poses geopolitical and environmental challenges. To meet the stringent 2030 EV market requirements ($>$ 450 Wh/kg, $<$ € 70/kWh, fast charging within 15 minutes), innovations must span across materials, manufacturing, system design, and recycling.

Looking forward, emerging technologies hold significant promise. SSBs could deliver step-changes in energy density and safety, although scalability and interfacial resistance remain unresolved. SIBs, while less energy-dense, offer cost and sustainability advantages due to the

abundance of sodium. LSBs provide the prospect of doubling the energy density of LIBs at lower cost, though their cycle life and safety issues remain critical hurdles. Even more radical are LABs, which could in principle achieve energy densities comparable to gasoline, although they are still constrained by fundamental challenges in reversibility and stability.

In summary, the future of EVs will depend on a multi-faceted approach: improving existing LIB chemistries, accelerating the development of innovative technologies, expanding recycling, EoL and second-life solutions, and implementing advanced safety strategies. Achieving these advances requires coordinated efforts in research, industry, and policy. If these challenges are successfully addressed, LIBs (and their successors) will enable EVs to reach higher levels of autonomy, reliability, and sustainability, playing an important role in the decarbonization of transportation.

9. Conclusions

This review provided a systematic examination of the key aspects of LIBs in EV applications, covering electrochemistry, performance, safety, recycling, and emerging technologies in a single, comprehensive framework. The main contribution of this work was to integrate these interrelated domains, offering a holistic perspective often missing in previous reviews focusing on isolated topics.

Our analysis showed that battery chemistry is the primary driver of EV performance, safety, and sustainability. In particular, cathode innovations such as LMFP and anode materials like Si/C composites demonstrated strong potential to enhance energy density, thermal stability, and cycle life, while also addressing cost and recyclability challenges.

By consolidating the current state of knowledge, this review identified critical areas for future research, including material optimization, enhanced safety measures, fast-charging capabilities, and sustainable EoL strategies. Achieving these advancements will be essential for supporting the widespread adoption of EVs and meeting the European and global decarbonization targets, making continued progress in LIB chemistry, materials, and system-level design crucial to accelerate the transition toward sustainable, high-performance electric transportation.

Abbreviations

ALISE	Advanced Lithium–Sulfur Battery Research Program
A-LSB	all Solid-State Lithium–Sulfur battery
BEV	Battery Electric Vehicle
BoL	Beginning of Life
BMS	Battery Management System
C-rate	Charge/Discharge Rate
CE	Coulombic Efficiency
CTP	Cell-to-pack
DoD	Depth of Discharge
e^-	Electrons
EIS	Electrochemical Impedance Spectroscopy
EoL	End of Life
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HE	High Energy
HEV	Hybrid Electric Vehicle
HP	High Power
ICM	Intercalation Cathode Material
IAM	Intercalation Anode Material
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
LAB	Lithium Air Battery
LCO	Lithium Cobalt Oxide
LIB/Li-ion	Lithium-ion Battery
Li^+	Lithium ions
LFP	Lithium Iron Phosphate
LMFP	Lithium Manganese Iron Phosphate
LMO	Lithium Manganese Oxide
LMNC	Lithium rich NCM
LMNO	Lithium Manganese Nickel Oxide
LNO	Lithium Nickel Oxide
LSB	Lithium Sulfur Battery
LTO	Lithium Titanate Oxide
MAB	Metal-air Battery
Na^+	Sodium ions
NCA	Nickel Cobalt Aluminium Oxide
NCM	Nickel Cobalt Manganese Oxide
NMCA	Nickel Manganese Cobalt Aluminium Oxide
OCV	Open Circuit Voltage
PHEV	Plug-in Hybrid Electric Vehicle
SEI	Solid Electrolyte Interphase
Si/C	Silicon/Graphite
SIB/Na-ion	Sodium-ion Battery
SoC	State of Charge
SoH	State of Health
SSB	Solid-State Batteries
TR	Thermal Runaway
VE	Voltage Efficiency

CRediT authorship contribution statement

Francesco Sciatti: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Tamburrano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elia Distaso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Riccardo Amirante:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonio V. Radogna:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arianna Morciano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giuseppe Grassi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Acknowledgements

This work was supported by the Ministero delle Imprese e del Made in Italy (MIMIT) - Health at Board (H@B) - under Grant CUP: B89J24002570005.

Data availability

No data was used for the research described in the article.

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