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A review of construction and sustainable recycling strategies of lithium-ion batteries across electric vehicle platforms

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The rapid adoption of electric vehicles (EVs) hinges on addressing two critical challenges of lithium-ion batteries (LIBs): thermal safety risks and end-of-life sustainability. This review provides a systematic comparison of LIB integration across four EV architectures including battery electric (BEV), hybrid (HEV), plug-in hybrid (PHEV), and fuel cell electric vehicles (FCEV), with a dual focus on mitigating thermal runaway and advancing recycling technologies. Through analysis of recent previous studies, we reveal three key findings: (1) battery pack configurations and thermal management systems across platforms; (2) thermal runaway mechanisms and mitigation strategies through case studies of field failures; and (3) emerging recycling methods achieve material recovery with lower energy input, though industrial-scale implementation remains challenging. Our meta-analysis identifies hydrometallurgy as the most viable near-term solution for LIB recycling (80–95% metal recovery), while highlighting promising alternatives like electrochemical relithiation that preserve cathode crystal structure. The work further examines critical infrastructure gaps, demonstrating that renewable-powered charging and localized recycling networks could reduce EV lifecycle emissions by 30–40%. By bridging materials innovation with systems engineering, this review provides a roadmap for developing safer, more sustainable LIB ecosystems from cell design to second-life applications, and prioritizes research directions for next-generation batteries compatible with evolving EV architectures.

1 Introduction

The global reliance on fossil fuels and the environmental degradation caused by internal combustion engine vehicles have spurred intensive research into advanced battery systems for electric and hybrid vehicles.[1–3] Lithium-ion batteries (LIBs) have emerged as the dominant energy storage solution, enabling EVs to reduce transportation-related CO_2 emissions by up to 70% compared to conventional combustion engine vehicles.[4] Beyond greenhouse gas reductions, EVs significantly decrease urban air pollutants such as nitrogen oxides (NO_x) and particulate matter (PM2.5), contributing to improved air quality.[5–9] Additionally, EVs exhibit a 3–5 dB reduction in traffic noise, mitigating noise pollution in densely populated areas.[10,11] However, widespread EV adoption faces critical challenges, including limited energy density,[12,13] supply chain vulnerabilities for key materials like lithium and cobalt,[14,15] and persistent safety concerns related to thermal runaway.[16]

Secondary batteries, specifically nickel–metal hydride and lithium-ion batteries, are widely recognized as the most technological advancement in rechargeable batteries. They have garnered a lot of attention and are currently the norm for many types of electric and hybrid cars.[17,18] The need for next-generation rechargeable batteries with high power, high capacity, fast charging rate, long cycle life, significantly better safety performance, and reasonable cost has become the prevailing focus in the electric and hybrid vehicle industry.[19] Additionally, it is anticipated that as electric car sales rise globally over the course of the forecast period, demand for electric vehicles equipped with rechargeable batteries will correspondingly rise.[20] The technology for electric vehicles is constantly progressing to meet demands for high performance and power density. In the upcoming years, electric and hybrid cars are expected to extensively utilize lithium-ion batteries.[21] The tendency is supported by the rise in fossil fuel prices and public awareness of EVs' benefits, which would ultimately encourage growth within the automotive application category.

Before LIBs—integrated EVs—dominated the commercial market, hybrid electric vehicles often used nickel–metal hydride battery generation to power the electric motor, sharing the load with the use of the internal combustion engine.[22] These are, of course, hybrid cars that use both electric and internal combustion engines with the aim of lowering travel costs, lowering emissions, and reducing reliance on charging stations.[23] Despite its notable reduction in greenhouse gas emissions, its inherently complex structure plays a role in gasoline engines, producing CO_2 during high-load conditions.

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The widespread commercialization of LIBs starting in the 1990s has led to a significant drop in the cost of these batteries, setting the stage for devices using this generation of batteries to be more widely used.[24,25] Until the expansion of hybrid cars using LIBs, the innovation of LIB has created the premise for radically revolutionizing the electric vehicle sector: replacing conventional combustion engines with highly efficient LIB-powered electric motors.[26,27] Batteries are currently used in a wide range of applications, primarily consumer electronics. Their advantages also transfer quite well to the stationary energy storage and electric mobility industries, including electric cars, motorcycles, scooters, bicycles, and advanced wheelchairs.[28,29] To claim that our lives today would be unimaginable without the use of batteries is not an exaggeration. Batteries are also considered a substitution for gasoline and other energy-related solutions, notably in the present automobile industry transformation.[3,30] In the 2030s, battery-powered electric automobiles are anticipated to revolutionize the future of transportation.[31]

Although electric cars still only account for a small portion of the overall automobile industry, their attractiveness is continuing to grow as automakers adopt modern technology to enhance EVs' performance and characteristics. One of the best zero-emission vehicles today, electric cars come in a variety of unique designs and pricing points. Currently, electric car types have evolved and been able to be customized to different market demands. Different types of EVs, such as full-battery electric vehicles (BEVs) and their commercial variations, including hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), in addition to another alternative fuel cell electric car (FCEV), have been extensively developed, appreciably reducing greenhouse gas emissions.[16] Compared to internal combustion engines (ICEs), EVs are considered more environmentally friendly, have higher energy efficiency, and have lower maintenance, fuel, and operating costs. How is an electric vehicle operated? The type of electric vehicle determines how it operates. Future developments and a quick discussion on the various types of electric vehicles and their operation will be provided in this review.

This review aims to systematically analyze four commercially prevalent electric vehicle types—BEVs, HEVs, PHEVs, and FCEVs, which focuses on their lithium-ion battery architectures, safety challenges, and sustainability trade-offs. While prior studies have investigated individual EV categories in isolation, such as BEV energy efficiency optimization[32–35] and lifecycle cost analyses,[36–38] a comprehensive, cross-category evaluation of lithium-ion battery (LIB) integration strategies remains underdeveloped, particularly regarding two critical aspects: (i) comparative thermal runaway mitigation approaches across EV architectures, and (ii) standardized frameworks for end-of-life battery management. This fragmentation hinders systematic progress in EV safety and sustainability. To address this gap, we employ a three-tiered methodology: (1) a meta-analysis of recent experimental data (2015–2023) on LIB performance across EV types, (2) a critical evaluation of thermal management systems and their failure modes, and (3) an assessment of recycling techniques through the lens of scalability and environmental impact. By synthesizing these dimensions, this work provides a roadmap for optimizing EV safety and circular economy practices, while identifying urgent research priorities for next-generation LIBs, including sodium-ion batteries, metal–air batteries, and all solid-state batteries.

2 The discussion for four commercial types of electric vehicles

2.1 Electric vehicle revolution with lithium-ion battery

The lithium-ion battery story began in 1960 with several reports on a new generation of batteries using CuF_2/lithium electrodes.[39–42] Until the 1970s, the interesting introduction of a TiS_2 electrode with high performance provided a promising future for commercialization at that time. However, it was limited by its high cost and hazardous generation of H_2S when exposed to ambient air.[43,44] A decade later, during the golden decades of the 1980s and 1990s, ground-breaking research, prolific patents, as well as the commercialization of lithium-ion batteries, were established. The introduction of two novel electrode materials, $LiCoO_2$ and graphite, along with the formation of a solid-electrolyte interphase that offers stable operation at high temperatures, increases battery life, and lessens explosive creation, has become a game changer.[45,46] The innovation led to the first commercialization of lithium-ion batteries in the 1990s, which fundamentally altered the portable electronics sector.

Fig. 1a presents a chronology of the evolution of lithium batteries, highlighting significant events at each stage, from the time it first emerged as an attractive option to the point at which it dominated the market for manufacture, distribution, and consumption. Fig. 1b illustrates the quality and time spent collecting batteries from three large markets in Europe, Australia, and the United States in 2012, when lithium-ion batteries became more popular and appeared in various devices.[47] The first generation of dry (low volumes of liquid) battery chemistries, such as lead-acid, zinc-carbon, and nickel–cadmium batteries, dominated much of the market.[48–50] Following the success of first-generation batteries, second generations were developed and commercialized with greater storage capacity, longer cycle life, and greater power density. The state-of-the-art has contributed to the electronic technology revolution of the early 20th century. These included numerous elite battery families, such as rechargeable alkaline batteries, including nickel–iron (NiFe) and nickel metal hydride (NiMH).[51,52] Nevertheless, rechargeable alkaline batteries have several challenges with energy density, recycling, flammability, thermal safety, and raising other environmental concerns.[53] These issues must be resolved by the following generation.

Currently on the market, there are many types of lithium-ion batteries obtaining their unique advantages and disadvantages that are utilized for diverse electronic devices. Typical battery cathode and anode chemistry comprises lithium cobalt oxide (LCO), lithium nickel oxide (LNO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide

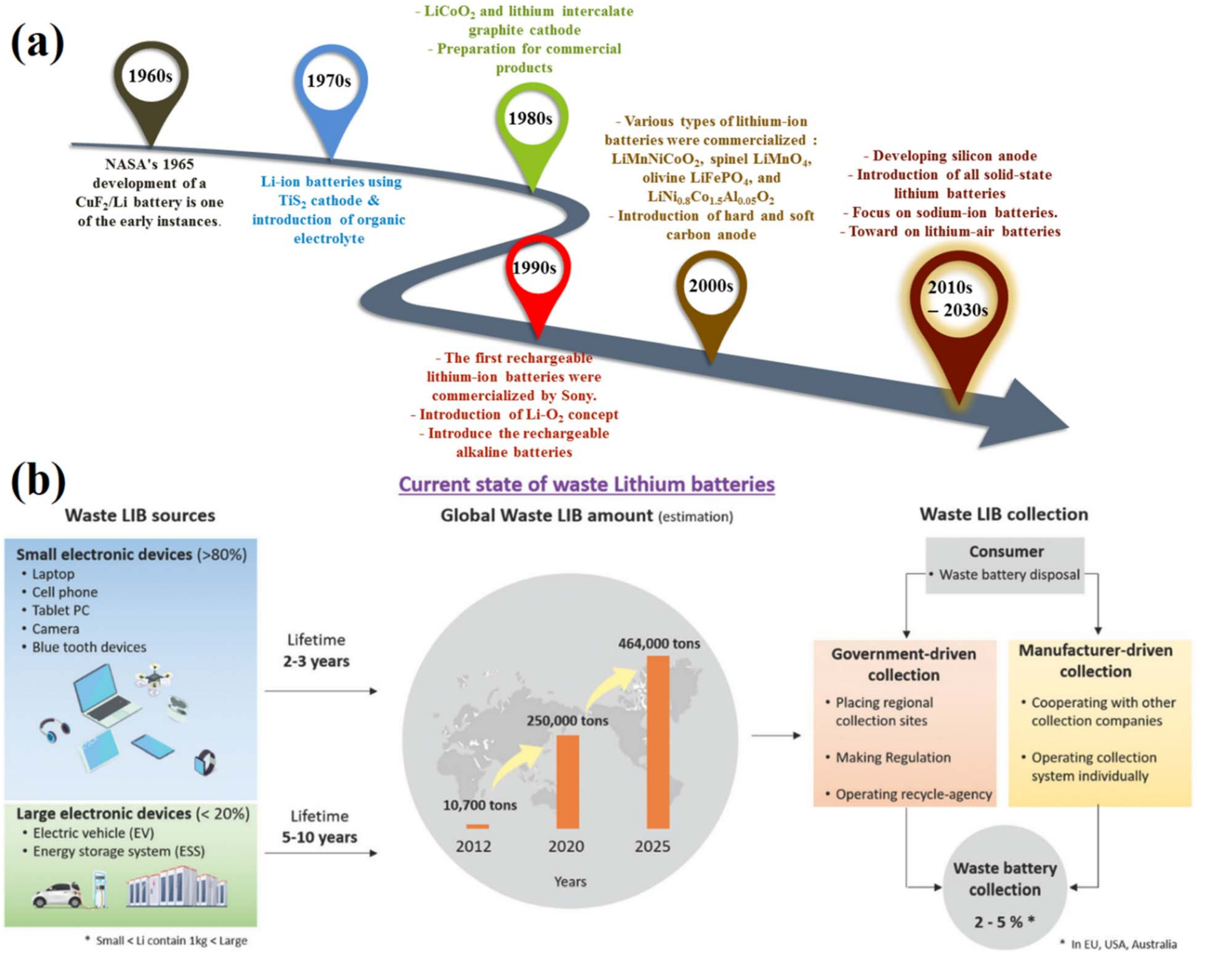

Fig. 1 (a) A timeline of lithium-ion batteries following (b) source, quality and spent batteries collection. Figure has been reproduced from ref. 47 with permission from Royal Society of Chemistry, copyright 2021.

(NCA), and, graphite anodes, silicon-based anodes, and lithium titanate (LTO) anodes.[54–58] Today, LIBs can be considered a widely commercial product. LIBs have gradually dominated the market, overwhelming the remaining generations owing to their outstanding performance. From tiny smart bracelets to truck-sized electric vehicles, LIBs have infiltrated our daily lives. Thereby, the dominance of LIBs will be long-lasting in the next decade, before the evolution of the next generation. However, this has triggered an unprecedented increase in demand for LIBs in terms of both quantity (number of cells) and quality (energy densities of cells). This leads to concerns regarding safety and the supply chain. Problems pertaining to thermal runaways and overmining critical mineral resources (such as copper, manganese, nickel, aluminum, cobalt, and zinc) are beginning to take center stage and can be arguably highlighted as some of the main hurdles for the research field to overcome. The increasing use and further development of LIBs have generated many consequences (resources and pollution) that need to be overcome and addressed as soon as possible. Thus, the next two parts will illustrate the brief of commercial lithium-ion batteries in electric vehicles in relation to the thermal runaway phenomenon and recycling.

2.2 Lithium-ion battery fabrication and package for electric vehicles

A commercial battery cell consists of the following main components: a cathode, an anode, and an electrolyte. Depending on the application, sub-components such as tabs, separators, current collectors, and housing cases can be varied in number and size. Lithium ions can be stored in cathode and anode layers during the discharging process, while electrolyte acts as a medium for lithium transportation (Fig. 2).[59] Typically, in a standard lithium-ion battery, the working mechanism of a lithium-ion battery can be simply explained by the charge and discharge processes. Under the charging voltage, lithium ions are created on the battery's cathode layer and are moved to the anode layer *via* the electrolyte. In the anode layer, the electrode, mainly made in porous form, is generally composed of different carbon forms or silicon that allow for lithium to be absorbed or alloyed, accommodating a large number of lithium ions within

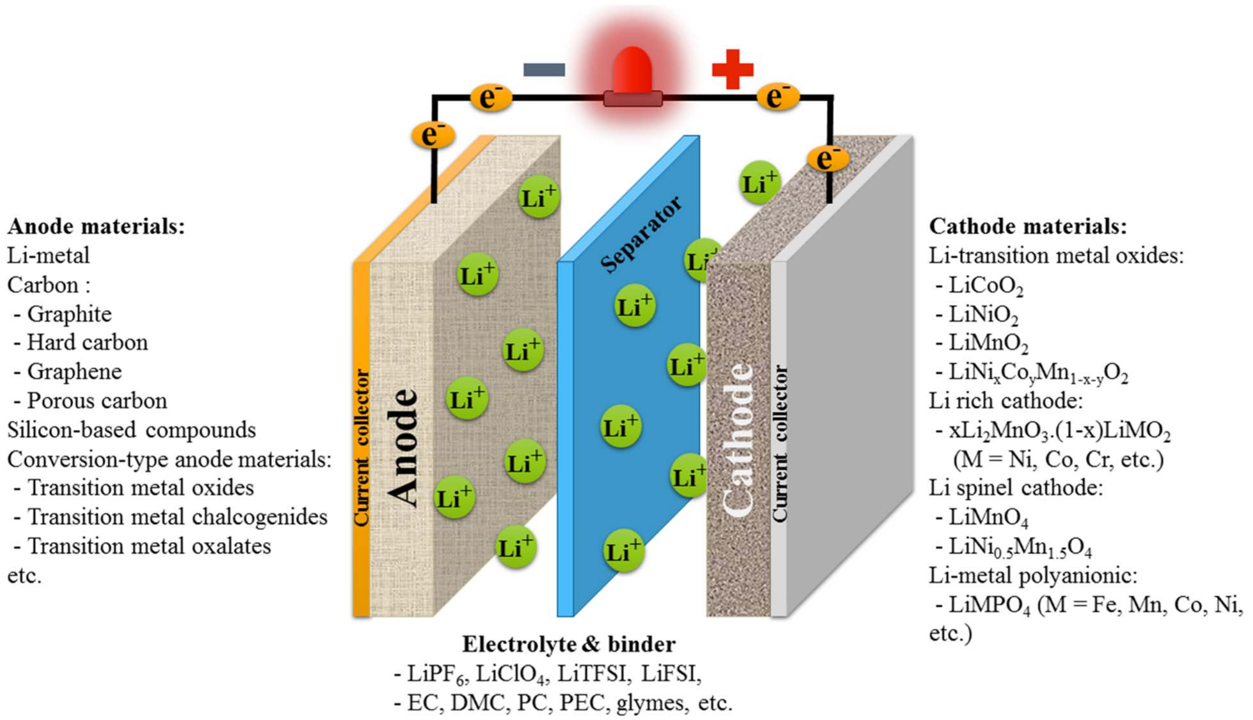

Fig. 2 (a) General construction of one lithium-ion battery cell with intensively studied electrode materials.

the structure. With more lithium ions stored, the charging capacity rises. In the discharge process and by providing electric current, the anode releases lithium ions to the cathode, creating electron flows from one side to another. That is, each Li ion moves from the anode to the cathode in the battery, and in the external circuit, there is another electron moving from the

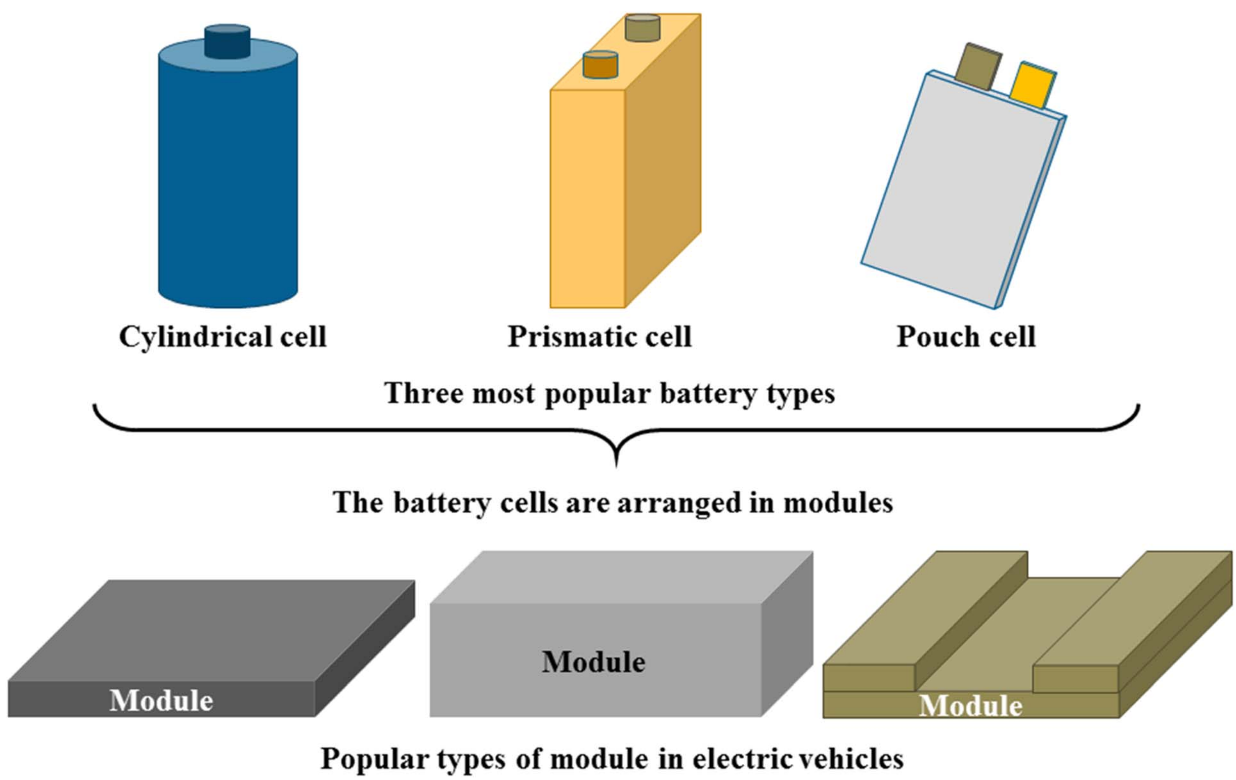

Fig. 3 The three most popular electric vehicle battery modules are based on three different cell types.

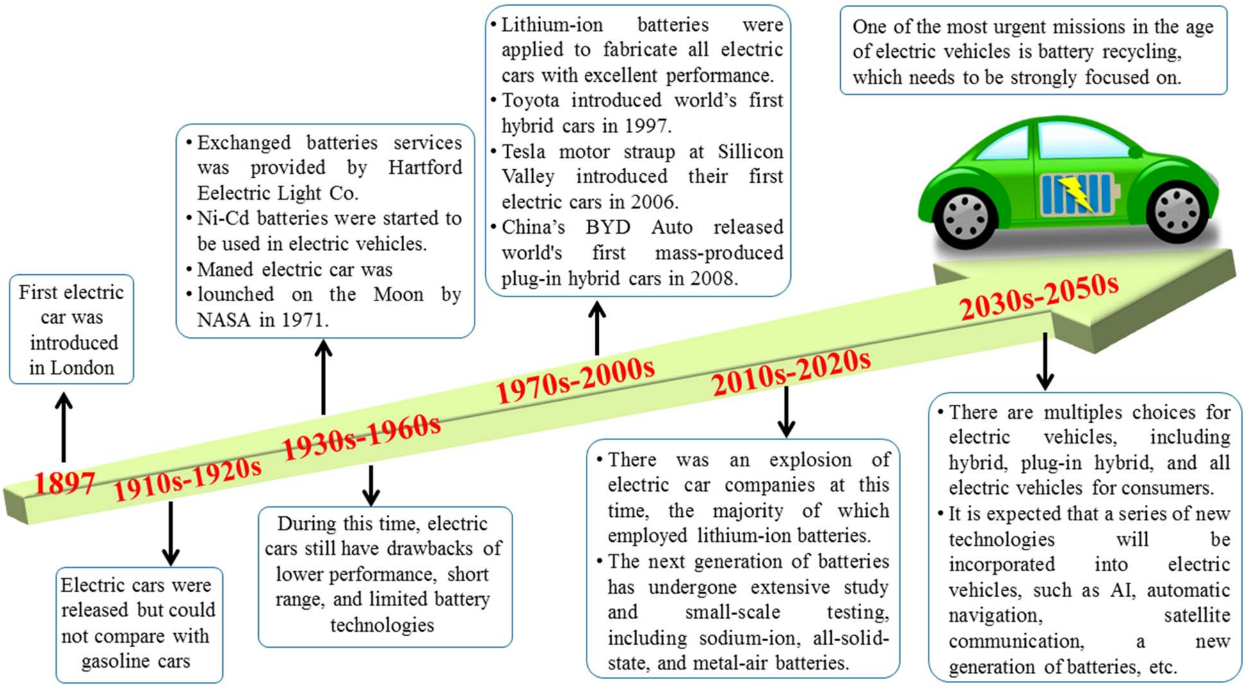

Fig. 4 A brief history and evolution of electric vehicles.

cathode to the anode, generating current flows. This creates a charge balance between the two electrodes.

Different manufacturers utilize different batteries in their electric vehicles. The chemical reaction in each of their batteries varies somewhat, but they are all basically constructed using the same battery cells and modules. Battery modules are constructed from an enormous number of cells, with the nominal voltage falling between 3 and 3.8 volts. These cells are connected in series or parallel to generate the required voltage and current. Currently, the primary lithium-ion battery configurations are cylindrical, prismatic, and pouch cell types, with each geometry exhibiting unique trade-offs in energy density,

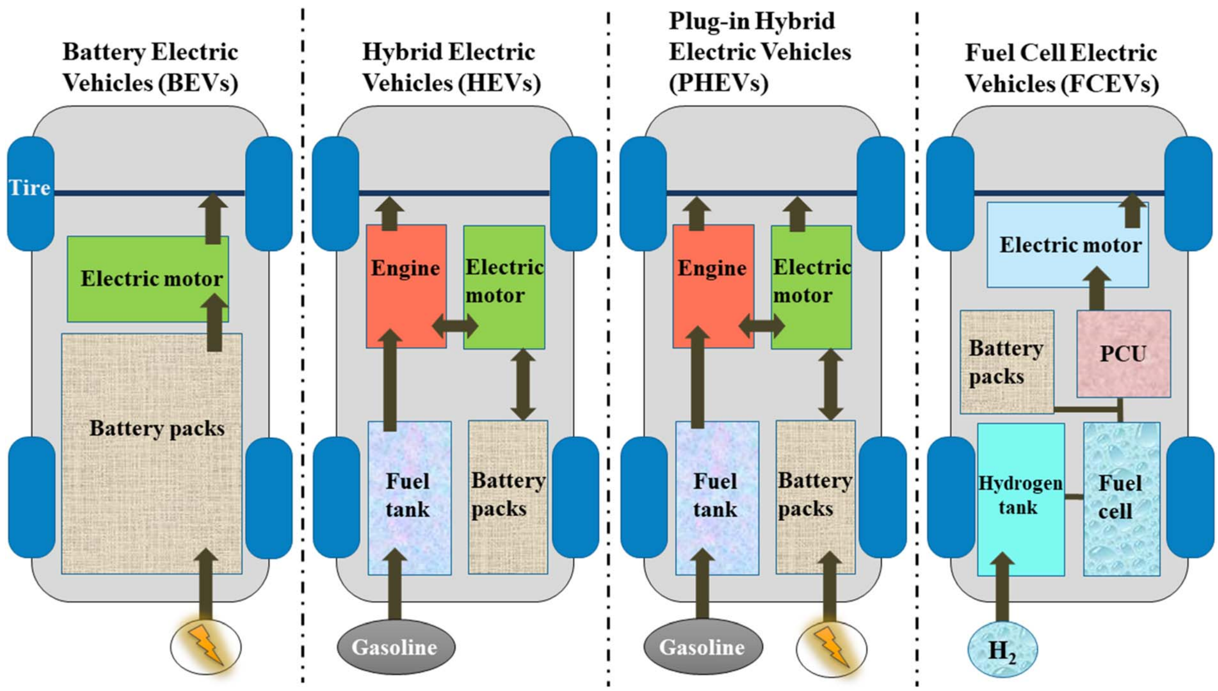

Fig. 5 The general construction of four most popular electric vehicles.

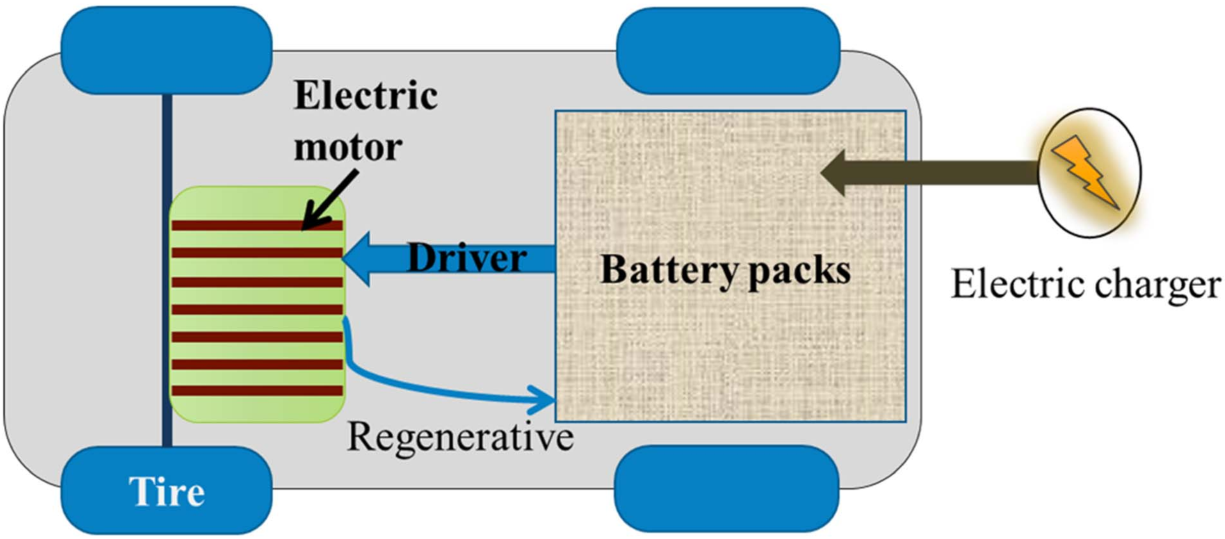

Fig. 6 Main components of battery electric vehicles.

thermal management, and manufacturability (Fig. 3).[60–63] The cylindrical cell batteries are mostly well known due to their low manufacturing costs, robust mechanical structure, streamlining processing, and high packing ratio (jelly roll-to-can ratio). The cylinder's drawbacks, however, are limited in available capacity and heat dissipation. To improve the operating capacity, prismatic cells were widely developed to adapt to applications calling for higher capacity. Each manufacturer develops their own format because they are made in a variety of sizes and have a box-like shape. Prismatic cells, because of their natural flat, rectangular shape, can achieve excellent power while improving thermal dissipation by having a high surface area and an increasing number of tabs for each layer (for stacking design). On the other hand, gas generation can be fatal as it builds up high internal pressure, damaging the housing case and jelly roll structure. As a consequence, severe thermal runaway is the highest priority in designing and developing these high-energy cells. The complex manufacturing process and higher cost per GWh, coming from "dead space" inside the cell, challenge OEMs to optimize. The newly developed type of aluminum-sealed-pouch cell is more flexible for packaging while enhancing the packing ratio (cell-to-module). This offers the advantage of being portable and able to fit into the little space inside the device, but it is particularly vulnerable to external stress and heat generation. Thus, the swelling and flammability that result from prolonged charge–discharge durations are two important issues with pouch cells. In fact, thermal runaway represents a critical safety risk across all lithium-ion battery configurations including cylindrical, prismatic, and pouch cells which though manifestation varies by design.[64,65] Cylindrical cells benefit from robust metal casings that may delay propagation, while prismatic cells' compact stacked electrodes and pouch cells' thin, flexible packaging accelerate heat transfer, increasing vulnerability to cascading failures.[66–68] Common triggers like internal shorts, overcharging, or mechanical abuse initiate exothermic reactions in any format, but pouch cells exhibit particularly rapid thermal spread due to minimal thermal mass between layers, whereas cylindrical designs may localize damage through built-in venting mechanisms.[69–73] These differences underscore that while no form factor is immune, understanding format-specific

Table 1 Battery type characterizations for electric vehicles. Table modified from ref. 85 with permission from jESE, copyright 2021[85]

Battery types	LCO	LMO	NMC	LFP	NCA
Cathode/Anode	$LiCoO_2$/graphite	$LiMn_2O_4$/graphite	$LiNiMnCoO_2$/graphite	$LiFePO_4$/graphite	$LiNiCoAlO_2$/graphite
Commercial time	1991	1996	2008	1996	1999
Voltage, V	3.0–4.2	3.0–4.2	3.0–4.2	2.5–3.65	3.0–4.2
Energy density, Wh kg^{-1}	150–200	100–150	150–220	90–120	200–260
Charge (C-rate)	0.7–1 C. Charge current above 1 C shortens battery life	0.7–1 C with maximum until 3 C, and charges to 4.2 V	Only from 0.7 to 1 C	1 C	∼0.7 C
Discharge (C-rate)	1 C. Discharge current above 1 C shortens battery life	1 C with maximum until 10 C for special versions	1 C	1 C	1 C typical
Cycle life, cycles	500–1000	300–700	1000–2000	2000	500
Thermal runaway, °C	150	250	210	270	150

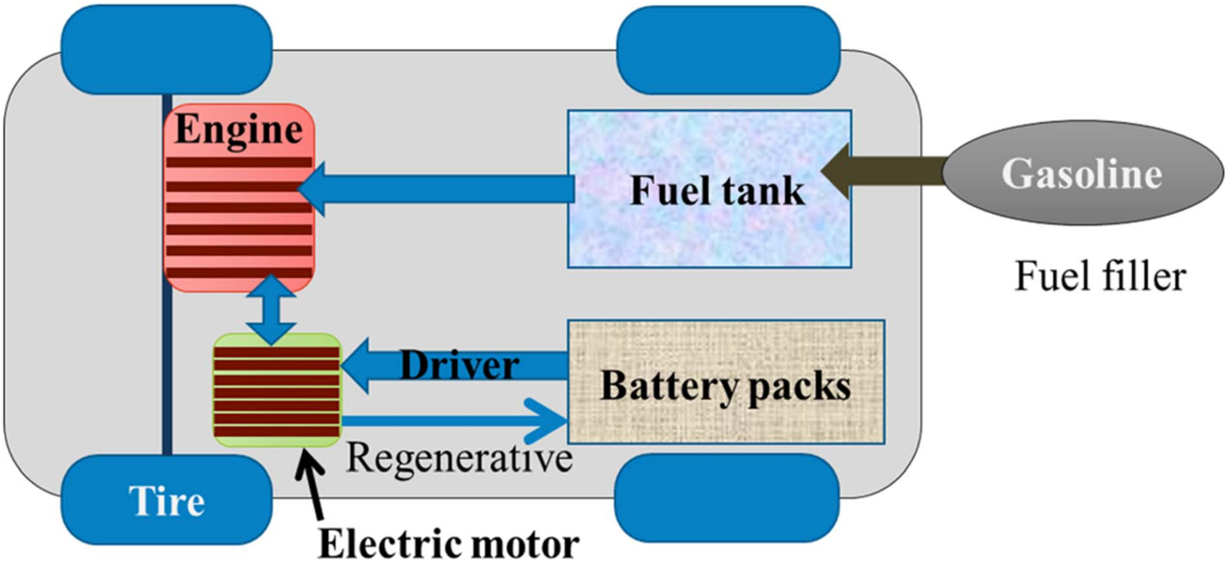

Fig. 7 Main components of hybrid electric vehicles.

failure modes is essential for tailored safety solutions in battery systems.

Fig. 4 presents a general timeline of the technological and commercial evolution of EVs from their experimental beginnings in the late 19th century to their projected market dominance in the mid-21st century. The earliest EVs presented in London during the 1890 s, utilizing nickel–cadmium (Ni–Cd) battery technology by Hartford Electric Light Company.[74] However, these early efforts were ultimately overshadowed by the rapid development of inexpensive, mass-produced gasoline vehicles, combined with the establishment of extensive petroleum infrastructure, which relegated EVs to niche applications for most of the 20th century. The modern renaissance of electric mobility began with several key milestones: NASA's deployment of the electric Lunar Roving Vehicle during the Apollo 15 mission in 1971 demonstrated the viability of battery-powered transportation in extreme environments.[74–76] The 1997 introduction of Toyota's Prius, the first mass-produced hybrid electric vehicle, marked a turning point in consumer acceptance of electrified powertrains. The subsequent decade witnessed critical technological breakthroughs, particularly Tesla Motors' 2006 Roadster, which proved lithium-ion batteries could deliver both performance and range, and BYD Auto's 2008 F3DM, the world's first mass-produced plug-in hybrid electric vehicle. Since 2010, multiple converging factors have driven unprecedented growth in EV adoption. Increasing environmental regulations, volatile fossil fuel prices, and dramatic improvements in lithium-ion battery technology (with energy densities

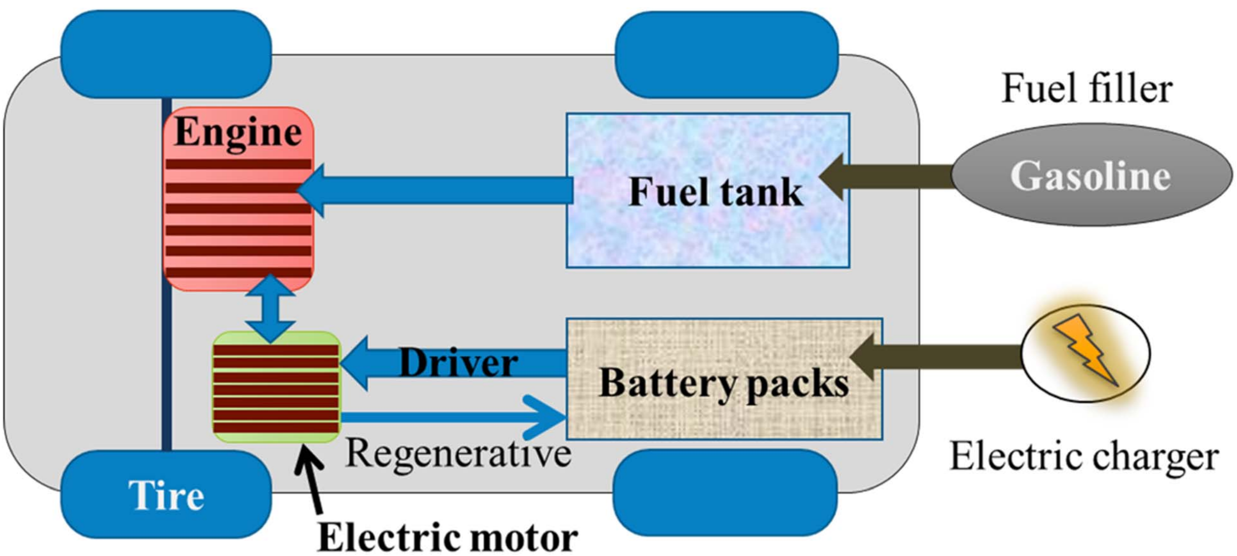

Fig. 8 Main components of plug-in hybrid electric vehicles.

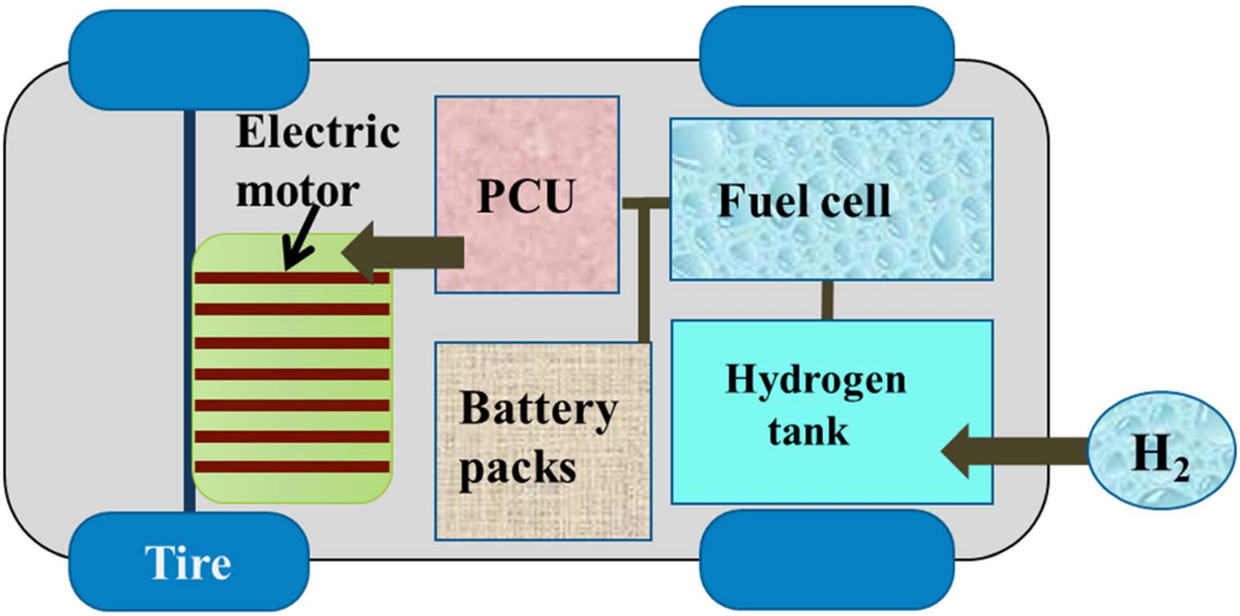

Fig. 9 Main components of fuel cell electric vehicles.

increasing by 5–8% annually while costs decreased by approximately 80% between 2010 and 2020) have transformed the automotive landscape.[77–79] Current research focuses on next-generation battery chemistries including sodium-ion, all-solid-state, and metal–air configurations that promise further improvements in safety, energy density, and sustainability.

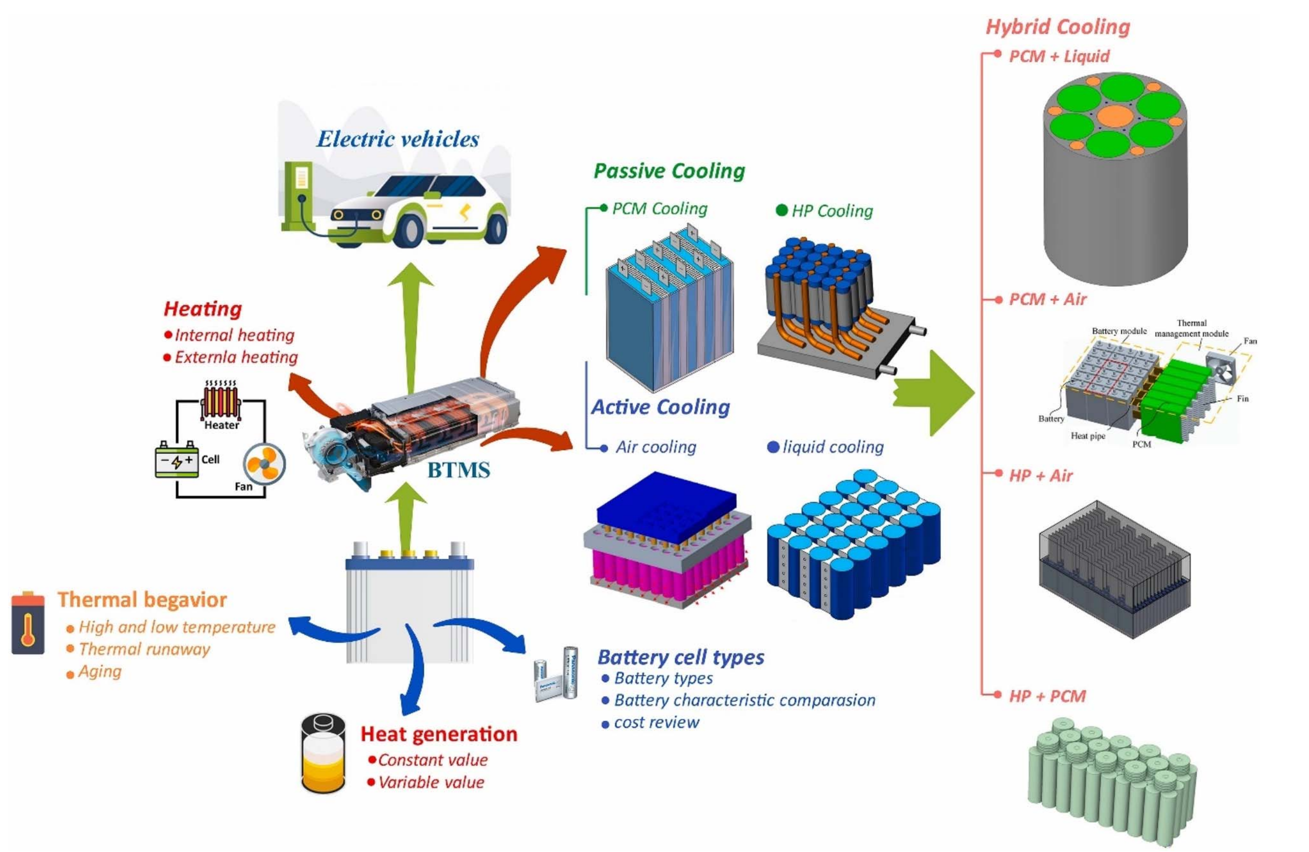

Fig. 10 An example of a hybrid thermal management system concept for a battery electric car that combines passive and active cooling systems with an emphasis on the battery pack. Figure has been reproduced from ref. 111 with permission of Elsevier, copyright 2018.

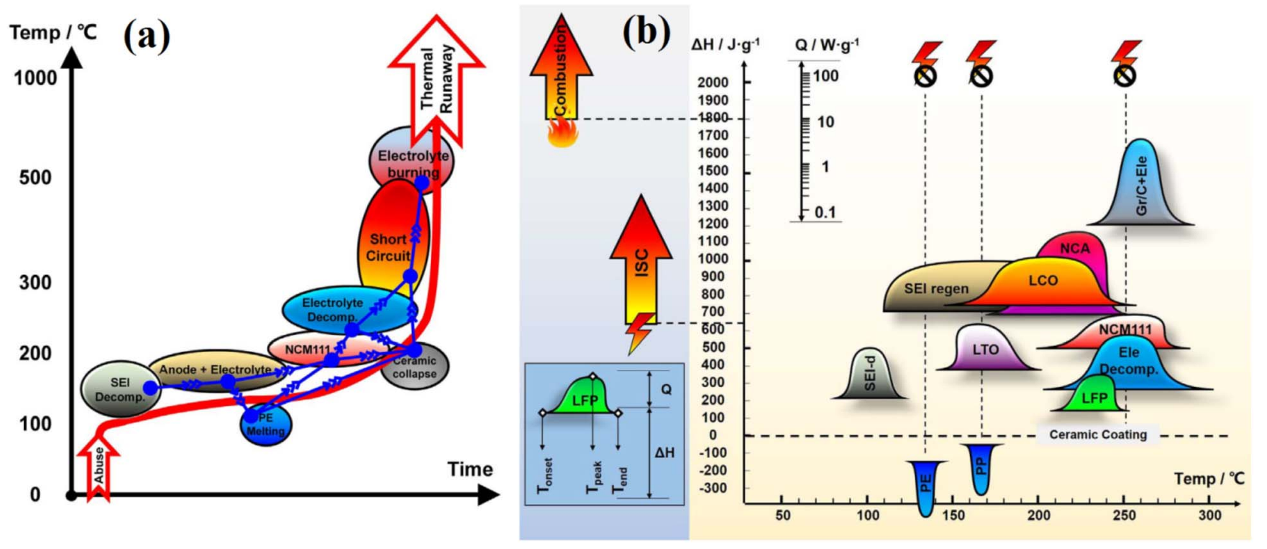

Fig. 11 (a) The quantitative chain reactions in thermal runaway, and (b) The typical differential scanning calorimetry (DSC) findings of the lithium-ion battery's component materials. Figure has been reproduced from ref. 124 with permission from Elsevier, copyright 2018.

Market projections indicate this growth trajectory will continue, with EVs expected to comprise 20% of global new car sales by 2025, increasing to 40% by 2030. However, complete market penetration faces challenges including the slow turnover of existing vehicle fleets – analysts estimate that even with 100% of new car sales being electric by 2040, approximately half of vehicles on the road may still use conventional powertrains due to the 10–15 years average lifespan of automobiles. This underscores the need for continued advancements in battery technology, expansion of charging infrastructure, and supportive policy frameworks to achieve full transportation electrification.

2.3 Introduction of four top commercial electric vehicles

Electric cars have gradually gained the trust of consumers with their affordable price, good performance, and reliable operation based on the recent rapid development of battery manufacturing technology. This is further supported by ground-breaking advancements in information technology, semiconductor technology, and telecommunications technology. In actuality, consumers' willingness to own electric cars is being driven by the expansion of available electric car models and the falling cost of batteries. There are currently four main categories of electric vehicles on the market: battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs) (Fig. 5).[80–83]

2.3.1 Battery electric vehicles. Battery-electric vehicles (BEVs) are fully powered by electric motors and rechargeable batteries. First developed in the 1880 s, early models served primarily as demonstrations due to technological limitations.[80,81] They became more viable in the early 20th century with improved batteries, replacing internal combustion engines with grid-charged battery systems. In general, BEVs have the following main parts: an electric motor, battery pack, inverter, control module, and drive train (Fig. 6). The electric motor serves as the primary propulsion device, converting electrical energy into mechanical energy to drive the vehicle, while the battery modules serve as the critical energy storage system that determines the range, performance, and operational capabilities. Most commercial BEVs today use rechargeable lithium-ion batteries due to their recyclability, higher energy density, and improved safety. The current state-of-the-art extensively focuses on three major types of cathodes, including layered structure types (lithium nickel oxide-LNO, lithium cobalt oxide-LCO, lithium nickel manganese cobalt oxide-NMC, NCA), spinel (lithium manganese oxide-LMO), and olivine (lithium iron phosphate-LFP), combining with different forms of anodes such as carbon forms (graphite, graphene), Si-based, and other possible carbon composites.[83,84] LIBs efficiently convert electricity into kinetic energy with minimal losses compared to combustion engines. However, they pose significant safety risks if thermal runaway occurs, leading to flammability and fire. This hazard makes thermal management systems critical for preventing thermal runaway, ensuring uniform temperature distribution, and reducing power degradation. Moreover, various cooling strategies have been developed to maintain optimal performance while meeting safety and environmental standards, while future advancements in electrode materials and electrolytes may further enhance energy density, lifespan, and high-temperature performance.

EV manufacturers each pursue customized lithium-ion battery solutions balancing cost, performance, and longevity. Current industry efforts focus on reducing production costs while maintaining battery capacity and lifespan. Table 1 compares five commercial EV battery types, highlighting their key properties. Among these, LFP (lithium iron phosphate) batteries offer distinct advantages: (i) superior thermal stability and safety from low resistance, and (ii) lower costs by avoiding

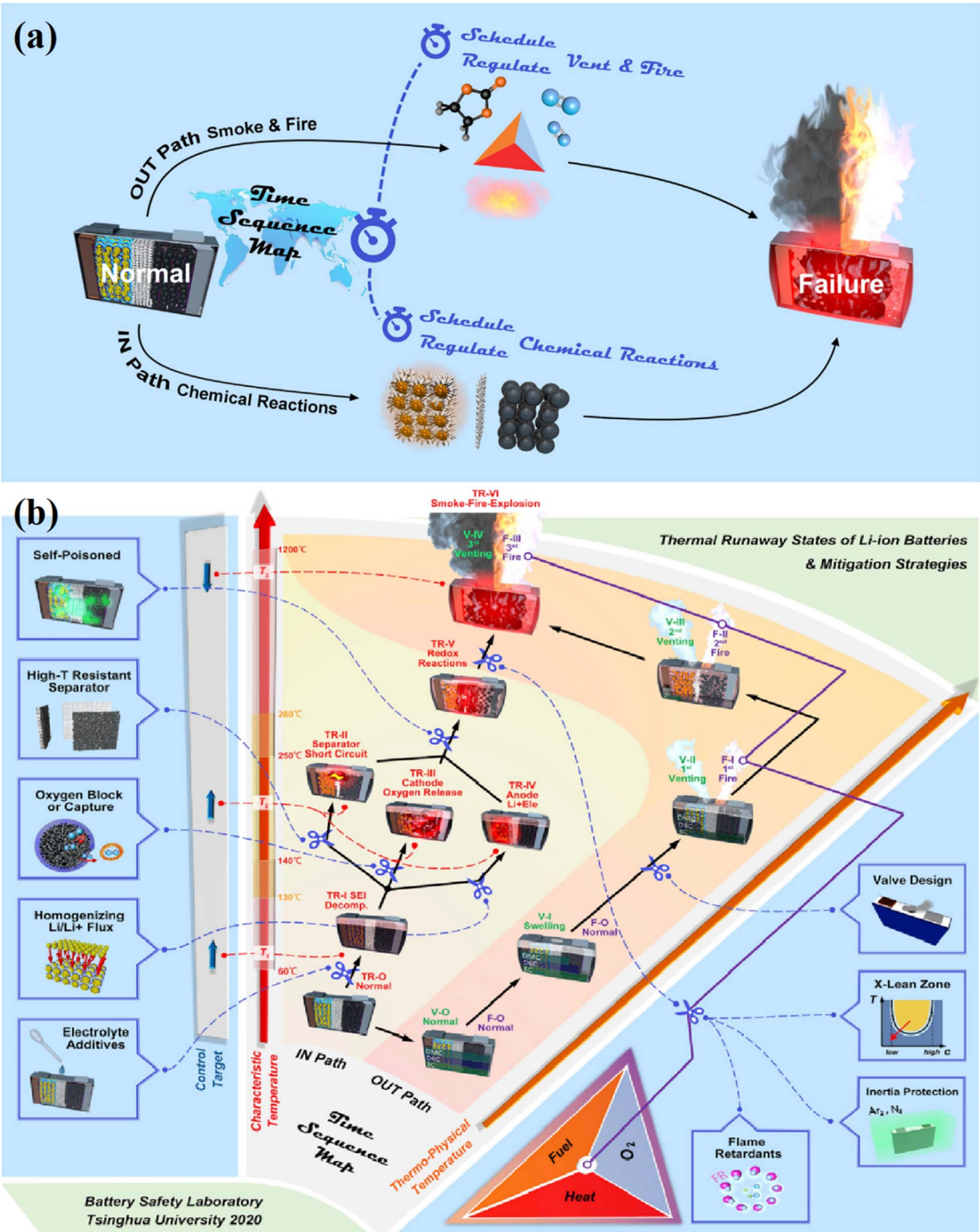

Fig. 12 LIB cell thermal runaway states and related mitigation techniques: (a) a description of the thermal runaway phenomena in the batteries and the concept of time sequence regulation, and (b) time sequence map based on characteristics temperature and thermal physical temperature. Figure has been reproduced from ref. 131 with permission from Elsevier, copyright 2020.

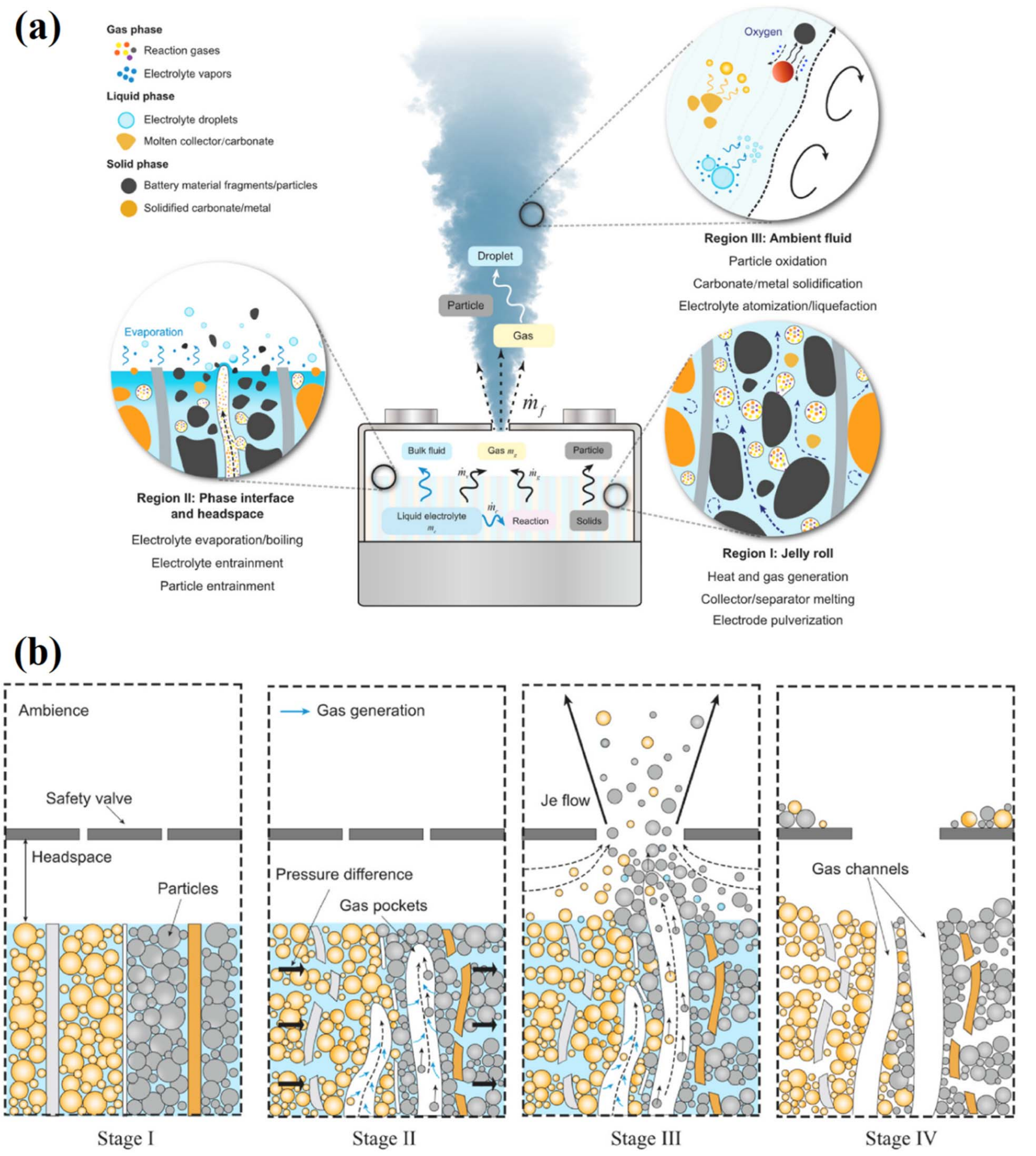

Fig. 13 (a) Diagram illustrating the mechanisms and change processes for the three main stages of thermal runaway, and (b) Particle release mechanism from a standard lithium-ion battery cell during thermal runaway. Figure has been reproduced from ref. 135 with permission from Elsevier, copyright 2023.

expensive cobalt, nickel, and manganese in their phosphate-based cathodes.

2.3.2 Hybrid electric vehicles. The hybrid electric vehicles (HEVs) employ both an electric motor and a gasoline engine to consume much less fuel while yet accelerating quickly.[86–88] Typically, hybrid electric vehicles are driven by a combustion engine as well as one or more electric motors that draw power from batteries (Fig. 7).[89,90] A simple hybrid electric vehicle cannot be plugged in to charge its battery. Instead, the battery is charged using a combination of regenerative braking and an internal combustion engine. The greater power provided by the electric motor may allow for a smaller engine. It is possible to lower the engine's idle usage while it is stationary and use the battery to power auxiliary loads. When combined, these

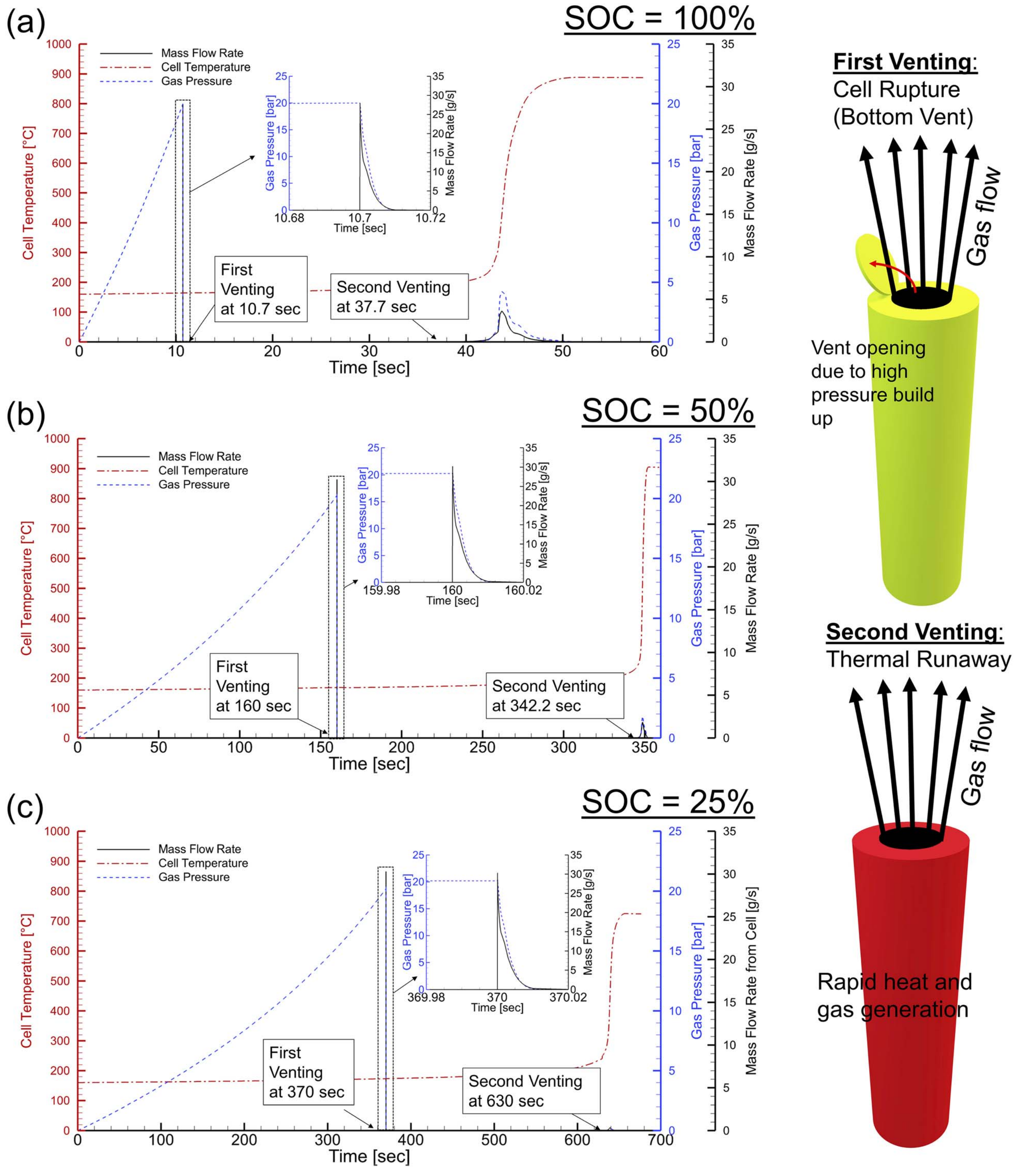

Fig. 14 The 18 650 battery cell under the temperature evolution of thermal abuse leading to gas pressure and mass flow rate at various states of charge (SOC): (a) SOC = 25%, (b) SOC = 50%, and (c) SOC = 75%. Figure has been reproduced from ref. 143 with permission from Elsevier, copyright 2021.

upgrades increase fuel economy while still maintaining a reasonable driving experience.

Despite the use of ICE, HEV resembles the same challenge as BEV when the system highlights the complex structure of different temperature control loops to balance temperature operation between the ICE, electric motor, power electronics, batteries, and cabin. The cost of replacements is high, but the lifespan of these batteries is quite long. The goal of eliminating fossil fuels in the future will lead to the replacement of hybrid electric vehicles by all battery electric vehicles, despite the manufacturers constructing newer hybrid cars with battery packs neatly stowed and saving space.

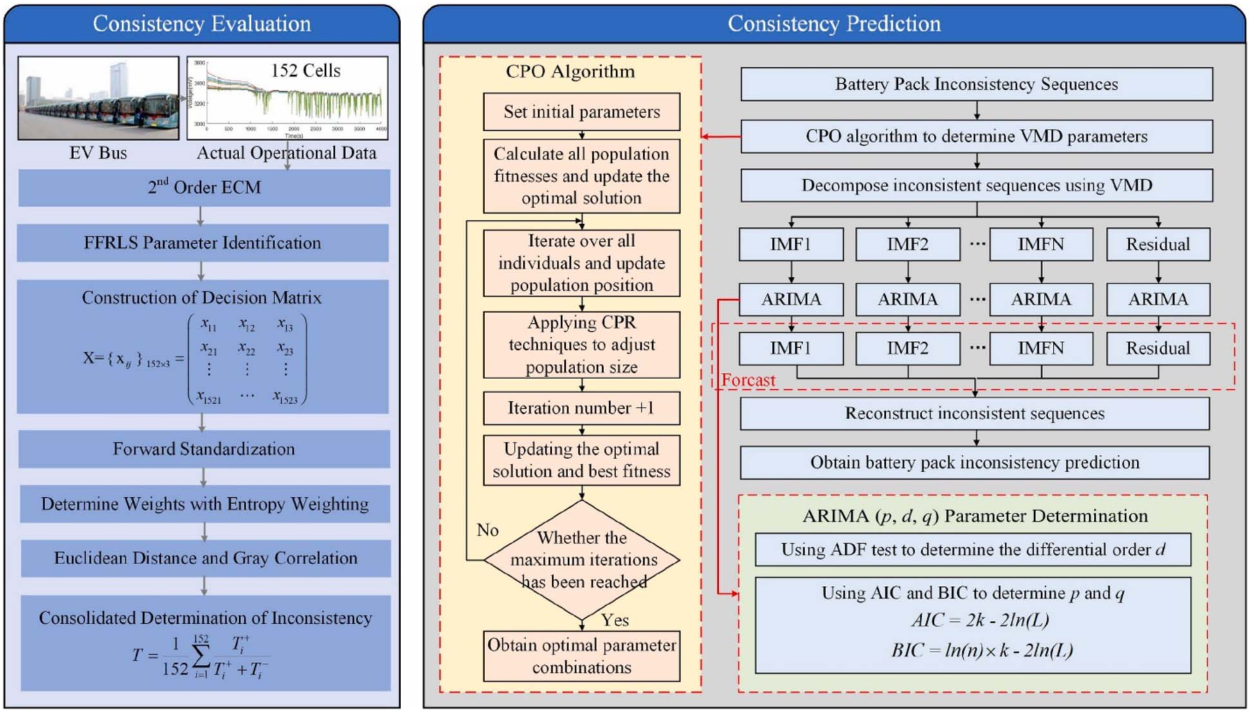

Fig. 15 Battery life time prediction based on actually operating data. Figure has been reproduced from ref. 187 with permission Elsevier, copyright 2025.

2.3.3 Plug-in hybrid electric vehicles. Plug-in hybrid electric vehicles (PHEVs) combine an electric motor (powered by rechargeable batteries) with a gasoline/diesel engine.[91] Their key feature is seamless switching between power sources – operating primarily on electricity until battery depletion, then automatically engaging the combustion engine (Fig. 8). The system can recharge batteries during operation, extending driving range while reducing fossil fuel consumption. However, PHEVs remain a transitional technology toward fully electric or fuel cell vehicles. Their dual powertrain introduces safety

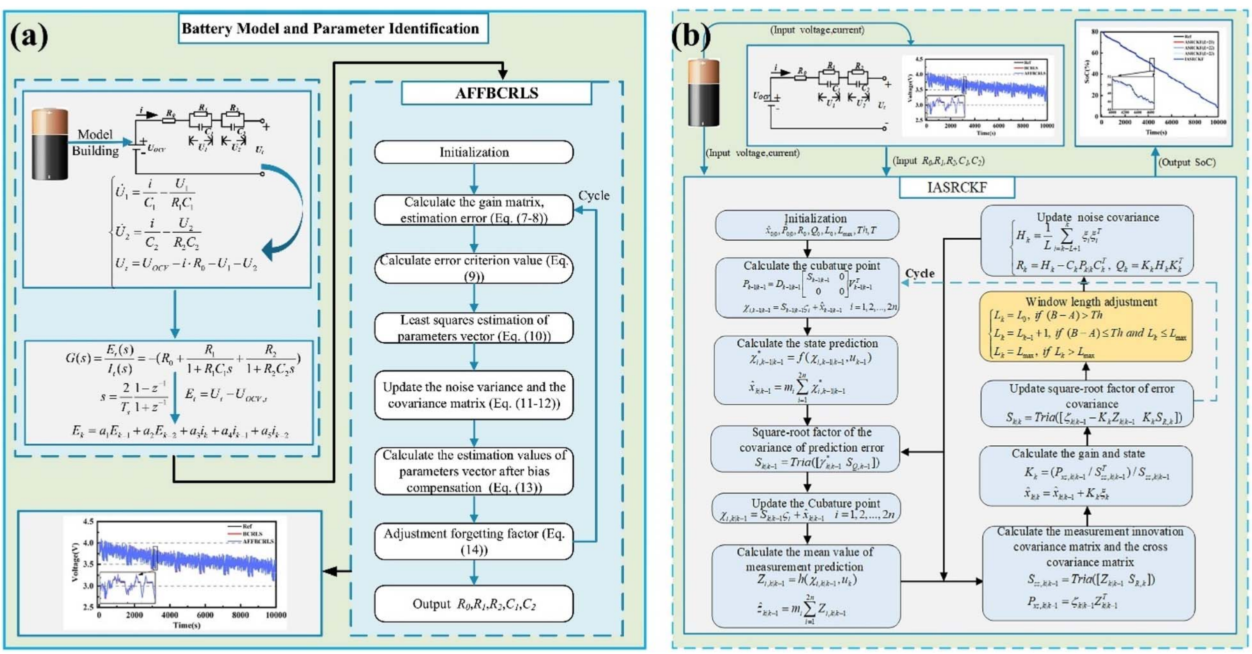

Fig. 16 The flowchart of (a) AFFBCRLS approach, and (b) IASRCKF method. Figure has been reproduced from ref. 198 with permission of Elsevier, copyright 2023.

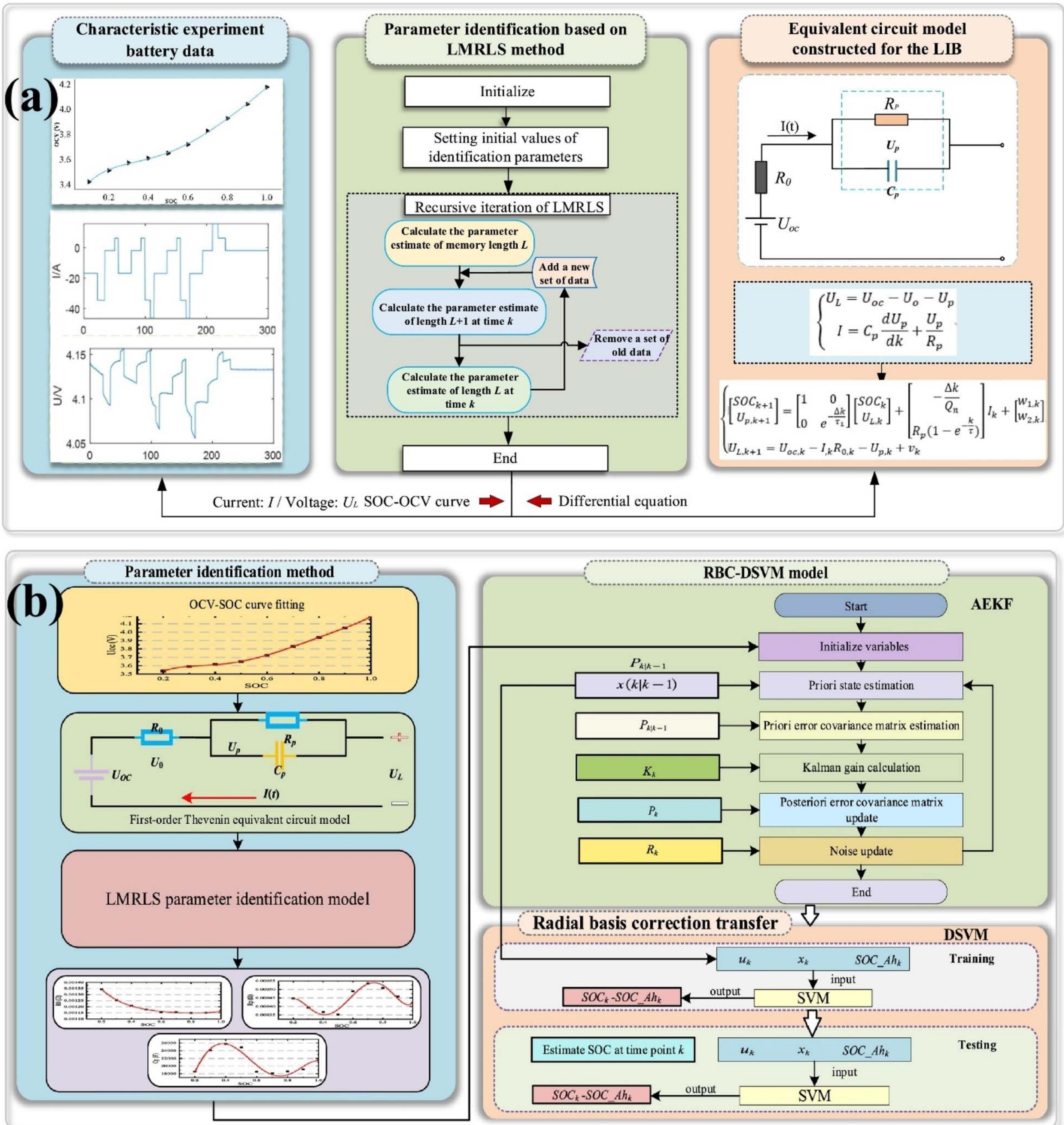

Fig. 17 Flowchart of (a) adaptive online parameter identification method and (b) RBC-DSVM model. Figure adapted from Wang *et al.*[199] Copyright 2024 Elsevier.

challenges, as high-capacity batteries combined with combustion systems may increase explosion risks due to reactive electrolytes. Despite these concerns, PHEVs currently offer a practical pathway to lower emissions and mitigate climate change impacts during the EV transition period.

2.3.4 Fuel cell electric vehicles. Fuel Cell Electric Vehicles (FCEVs) employ an electric motor powered primarily by a fuel cell system controlled by a Power Control Unit (PCU) (Fig. 9).[92] LIBs serve as complementary energy storage, functioning as power buffers during high-load conditions (*e.g.*, acceleration) while enabling regenerative braking. This dual-system architecture improves energy efficiency by: (i) mitigating peak loads on fuel cells to extend durability, (ii) optimizing power distribution, and (iii) recovering braking energy. Unlike combustion engines, FCEVs emit only water vapor and heat and avoid efficiency limitations of the Otto cycle through electrochemical potential-based operation.[93] While promising for next-generation mobility, FCEVs face infrastructure challenges due to underdeveloped hydrogen production and distribution networks. Compared to BEVs, FCEVs offer advantages in

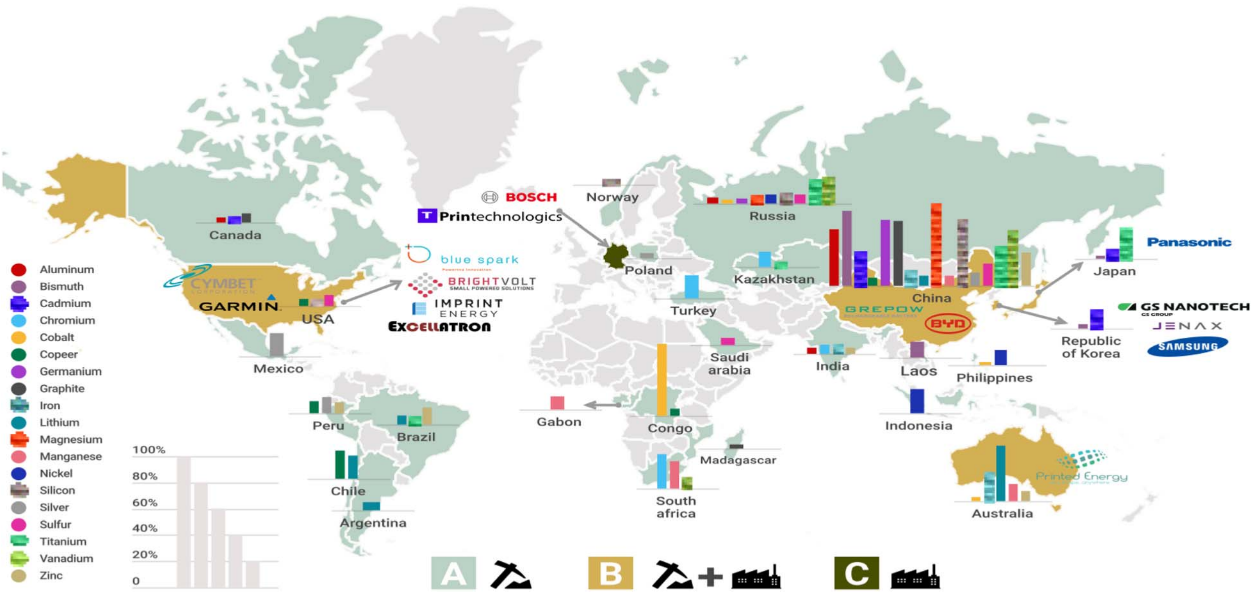

Fig. 18 Production of lithium-ion battery materials worldwide. Fig. 15 adapted from Pantoja *et al.*[200] Copyright 2022 MDPI.

refueling speed with fast-charging by few minutes for a long range, making them suitable for heavy-duty transport.[94,95] However, BEVs currently benefit from established charging infrastructure, higher well-to-wheel efficiency (60–80% *vs.* 25–35% for FCEVs), and lower operating costs.

Hydrogen, the energy fuel of FCEVs, can be produced through multiple methods, categorized as fossil fuel-based, such as steam reforming or partial oxidation or renewable-based (electrolysis, biomass conversion).[96] While steam methane reforming remains the dominant method (50% of global production), its high CO emissions limit sustainability.[96] Renewable methods are increasingly attractive due to lower emissions and abundant feedstock availability. As the hydrogen economy expands, these green production methods will be crucial for enabling sustainable fuel cell electric vehicles and reducing fossil fuel dependence.

2.3.5 Thermal management systems onto different EVs. Each of the four vehicles mentioned above contains a thermal

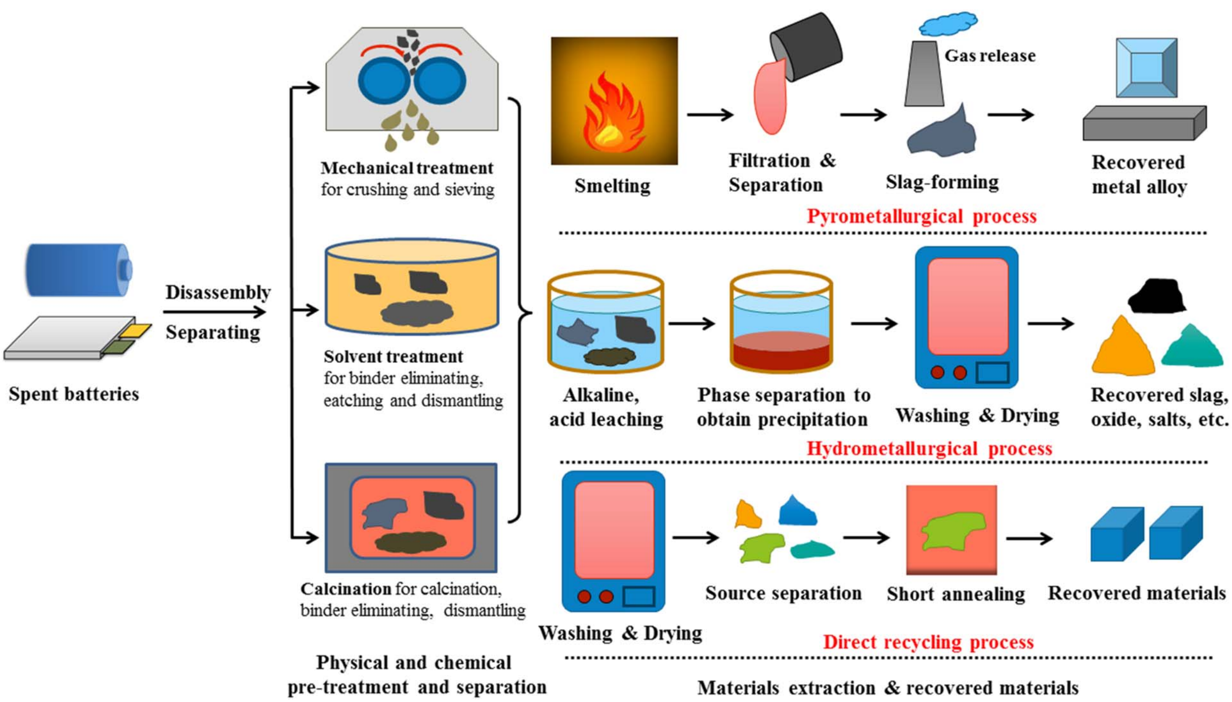

Fig. 19 General process to recycle lithium-ion batteries, including pyrometallurgical, hydrometalurgical, and direct recycling methods.

Table 2 Advantages and disadvantages of the three main battery recycling methodologies

Techniques	Direct recycling method	Pyrometallugical method	Hydrometallugical method
Advantages	- Suitable for almost batteries types	- Can recycle a large number of spent batteries	- High selectivity and high recycling efficiency and value-added products
	- Short recovery path and easy to operate	- Can recovery of the high quality precious metals	- Low working temperature
	- Low-cost due to low energy consumption, and high recovery rate	- Small chemical consumption	- High effectiveness at removing other contaminants
	- Environmental friendliness	- Short flow and straightforward procedure	- Can recover almost cathodic materials
			- Rezo SO_2 gas emissions
Disadvantages	- Take a time for mechanical pretreament and separations	- High investment costs	- Nonenvironmental friendly wastewater after productions
	- Mixing cathode materials may be reduced the quality of recycled materials	- High energy requirements due to high required temperature	- Incomplete binder and electrolyte recycling
	- Recycled materials may not good as virgin materials	- The discharge of hazardous gases into the environment	- Procedure complexity
		- Losing lithium materials	- Chemical selectivity

management system (TMS), which is a crucial component with the shared objective of maximizing durability, safety, and performance. However, each of TMS has its own unique features. In BEVs, TMS focuses primarily on lithium-ion battery packs, employing liquid cooling or refrigerant-based systems to maintain optimal temperatures during charging/discharging, while also managing motor/inverter heat.[97,98] HEVs integrate dual cooling systems for both the internal combustion engine (ICE) and the battery/motor system, often prioritizing ICE thermal needs due to smaller battery capacities.[99–101] PHEVs have more complex challenges, requiring adaptive TMS to balance high-voltage battery cooling (during electric mode) with ICE waste heat recovery (during hybrid mode), while preventing thermal interference between systems.[102–106] In general, FCEVs demand triple thermal regulation: (i) cooling the fuel cell stack *via* liquid coolants, (ii) managing lithium-ion buffer battery temperatures, and (iii) handling cryogenic hydrogen storage heat exchange.[107–110] All EV types utilize advanced control strategies, such as predictive algorithms and phase-change materials, to mitigate thermal runaway risks, reduce parasitic energy losses, and extend component lifespans. While BEVs/PHEVs emphasize battery-centric cooling, FCEVs require integrated chemical/electrical thermal management, reflecting their unique energy conversion processes. Emerging solutions like heat pump integration and unified cooling plates are being adopted across platforms to improve efficiency and adaptability to extreme climates. Fig. 10 illustrates a typical diagram of the components of the energy management system in an electric vehicle with active and passive cooling systems centered around the battery pack system.[111] While passive cooling systems using phase change material (PCM) and heat pipes (HP) are popular due to their low cost but poor heat dissipation under conditions of high system temperature and lack of control system. Active cooling systems can be controlled and have the ability to dissipate heat quickly but also have the limitation of consuming a lot of operating energy and causing costly maintenance due to their complex structure. Therefore, hybrid systems between passive and active are developed to optimize the overall cost as well as the life of the system.

2.4 Battery thermal runaway phenomenon in battery electric vehicles

Safety remains one of the most critical challenges hindering the widespread adoption of LIBs in EVs. As energy densities continue to increase following the increase of battery module, ensuring LIB safety becomes increasingly imperative. The primary safety concern involves thermal runaway – a potentially catastrophic failure mode resulting from sequential, thermally-activated degradation processes of battery components through chain reactions.[112] This section examines the underlying chemical mechanisms driving thermal runaway in commercial lithium-ion battery systems, with the aim of providing a comprehensive analysis of this critical safety phenomenon and its mitigation strategies. Following the timeline from 2020 to mid-2025, there have been thousands of electric vehicle fires and explosions worldwide, with the largest number occurring in the two largest electric vehicle markets, China and the United States.[113–116] However, the exact number in specific accident situations in the world is difficult to determine due to the confidentiality of electric vehicle manufacturers and political factors. It can be seen that the number of electric vehicle fire and explosion accidents is lower than that of gasoline vehicles, however, with the remarkable growth of electric vehicles in the coming years, the safety of electric vehicles when operating and charging has raised certain concerns from consumers. Next, the thermal runaway phenomenon is discussed as the suspected cause of the explosion of the battery pack, causing the entire electric vehicle to catch fire.

Lithium-ion batteries typically maintain a stable structure due to the reversible movement of lithium ions between the cathode and anode during standard charging and discharging cycles. However, in mechatronic systems employing large

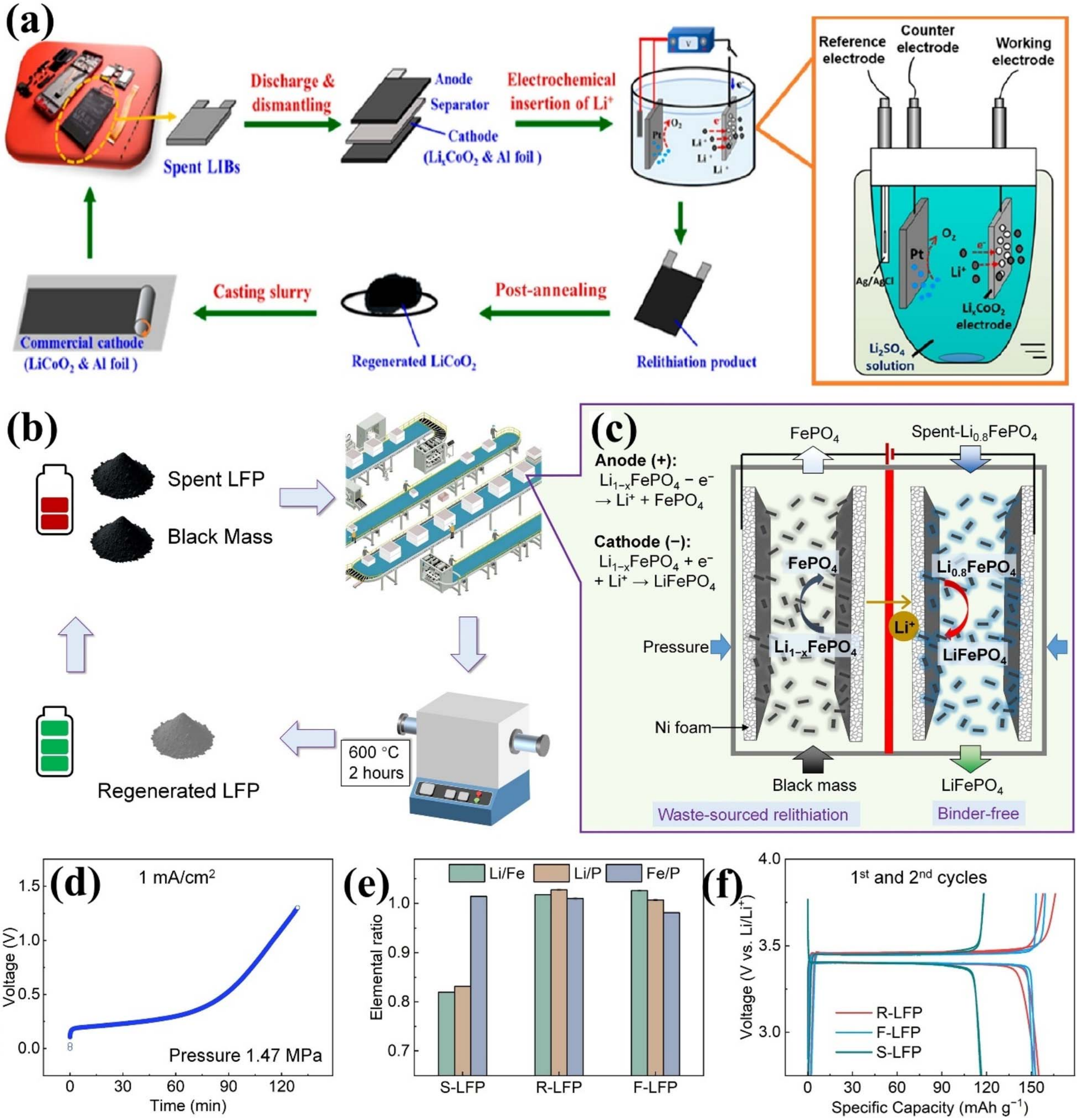

Fig. 20 (a) Schematic representation of the cathode regeneration technique, where electrochemical lithium reintegration transforms spent Li_xCoO_2 electrodes into reusable $LiCoO_2$ active materials for new batteries, and thick-electrode regeneration of spent battery materials: (b) schematic overview of the thick-electrode regeneration process for spent lithium-ion batteries, (c) electrochemical relithiation mechanism enabled by thick-electrode architecture, (d) voltage–time profile during constant-current relithiation, (e) compositional analysis (Li/Fe, Li/P, and Fe/P atomic ratios) of regenerated $LiFePO_4$ (LFP) powders, (f) comparative cycling performance (1st *vs.* 2nd cycle) of regenerated LFP in coin cells. (a) has been reproduced from ref. 230 with permission from American chemical society, copyright 2017. (b–f) has been reproduced from ref. 232 with permission from Elsevier, copyright 2025.

lithium-ion battery arrays, such as electric vehicles, various operational factors can initiate thermal runaway in the battery system. When the battery cells have a thermal runaway phenomenon, it can be extremely difficult to stop the chain reaction from continuing. This phenomenon occurs when the internal temperature rises to a point of chemical reaction appearance, increasing temperature in the overall cell, which in turn triggers other chemical reactions that release even more heat. The battery cell temperature increases exponentially within milliseconds as stored energy is abruptly released under abusive conditions. This uncontrolled exothermic process generates sequential chain reactions capable of reaching temperatures exceeding 400 °C, with potential escalation to 1000 °C. At these elevated temperatures, the cell typically

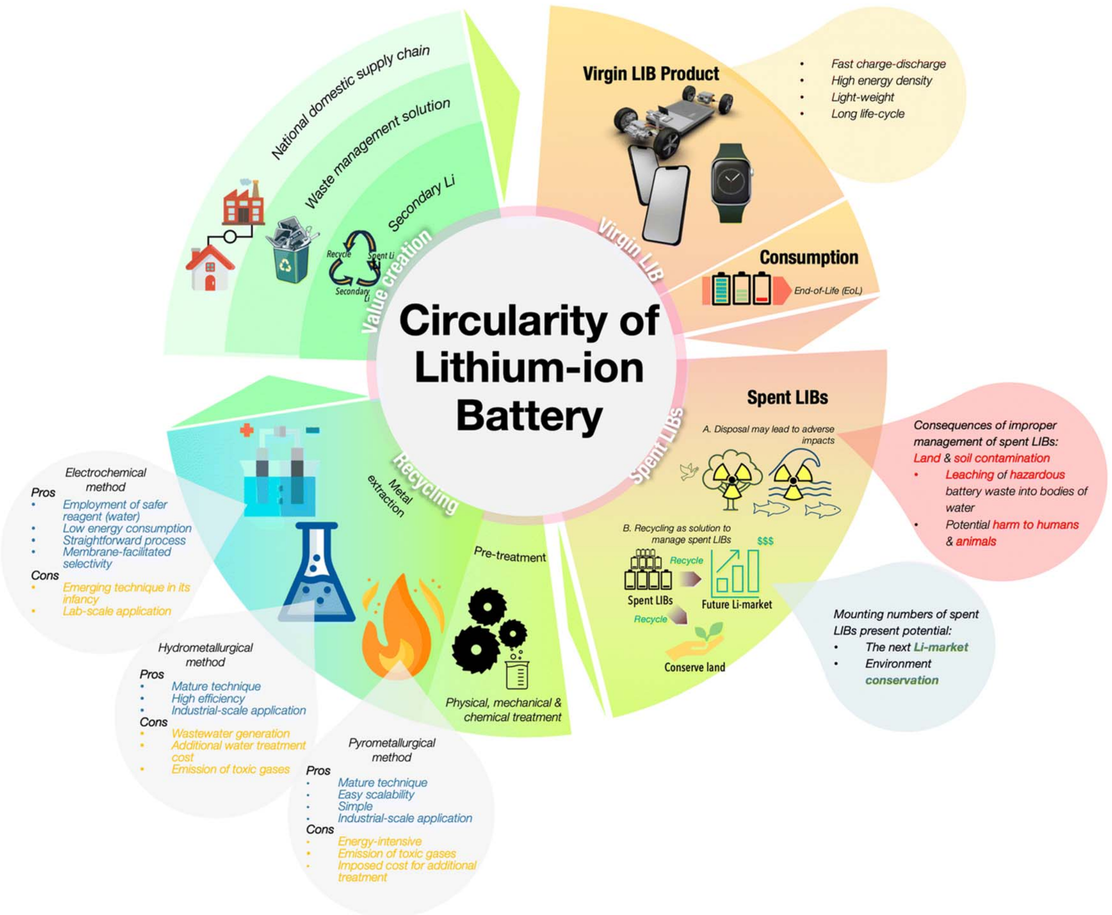

Fig. 21 The schematic illustrates a complete circular economic cycle for lithium batteries, starting from their use in electric vehicles to typical end-of-life battery recycling processes and recovery of valuable materials for reuse. Figure 21 has been reproduced from ref. 245 with permission from Royal Chemical Society, copyright 2024.

undergoes violent venting of flammable electrolytes, creating self-sustaining fires that resist conventional suppression methods. Typically, the thermal runaway can be divided into four stages: (i) from 80 to 120 °C: as the temperature increases, electrolyte and solid electrolyte interphase (SEI) components start to decompose. The newly exposed electrode particle area promotes further reactions with electrolyte, losing lithium inventory and creating more SEI that increases the resistance of the battery; (ii) over 140 °C: the exothermic reactions of cathode materials with releasing oxygen; (iii) over 180 °C: the decomposition of both cathode and electrolyte layers; and (iv) the batteries are completely destroyed.[117–119] In the actual use of electric vehicles, many factors have been recorded that lead to the phenomenon of thermal runaway. In general, there are three main factors classified as follows: (1) mechanical abuse (physical damage by crash, puncture, penetration, collision, *etc.*); (2) electrical abuse (overcharge/discharge, internal short circuit, *etc.*); and (3) thermal abuse (overheating, flame attack, *etc.*).[120–123]

What might be the initial cause of thermal runaway? The internal process of thermal runaway is primarily brought on by a series of exothermic chain reactions. In other words, because the heat generated by the side reactions in the previous stage cannot be completely dissipated in time, the battery temperature will increase. As a result, the temperature increase may start a subsequent round of adverse reactions, finally resulting in thermal runaway. Studies have demonstrated the side reactions that occur during the thermal runaway of lithium-ion batteries, such as the SEI decomposition, anode-electrolyte reaction, separator melting, electrolyte decomposition, cathode decomposition (dissolution of transition metal, lithium plating/dendrite causing short circuit, oxygen release), short circuit, and electrolyte burning (Fig. 11a).[124,125] For detail, Fig. 11b shows the typical differential scanning calorimetry (DSC) findings of the lithium-ion battery's component materials. The heat release power (Q), the enthalpy (ΔH), which reflects the total heat released, and the distinctive temperatures, such as the onset temperature (T_{onset}), the peak temperature (T_{peak}), and the terminal temperature (T_{end}), are among the features of the processes.[124,126] The heat release for typical battery materials has been outlined, and it has been discovered that the beginning temperature for commercial cathode materials is as follows: $LiFePO_4$ (LFP) > $Li_4Ti_5O_{12}$ (LTO) > $LiNi_xCo_yMn_zO_2$ (NCM) > $LiNi_xCo_yAl_zO_2$ (NCA) > $LiCO_2$ (LCO).[127] The

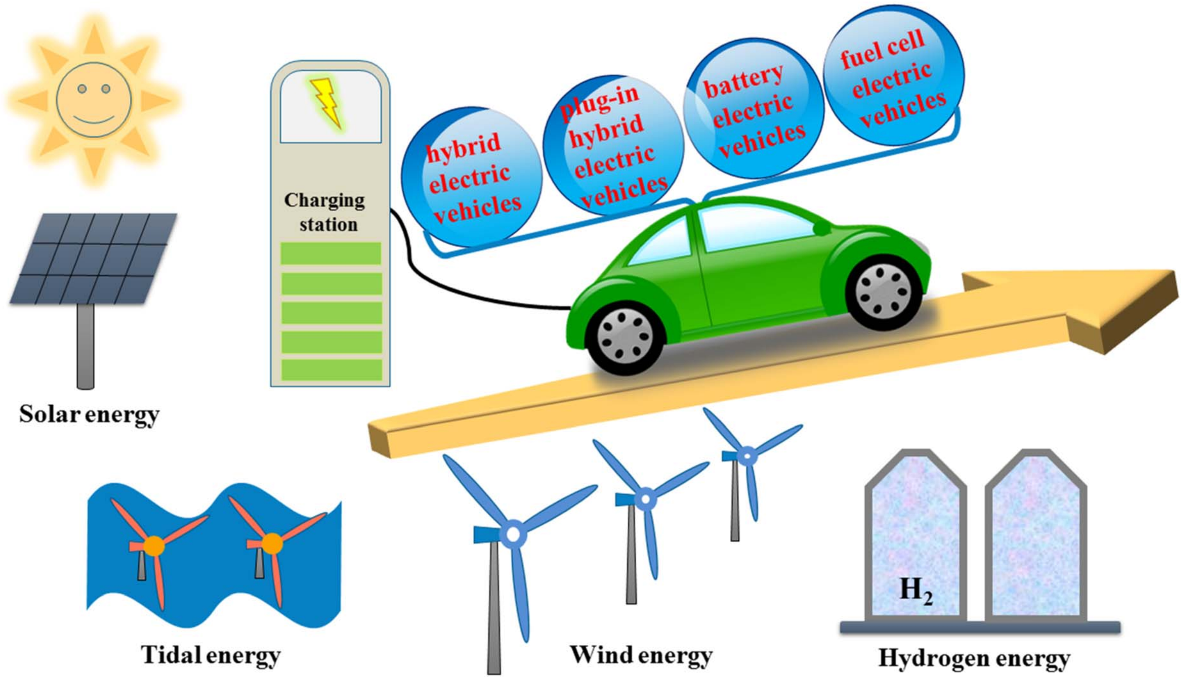

Fig. 22 The promising goal for electric vehicles is to use renewable energy for charging.

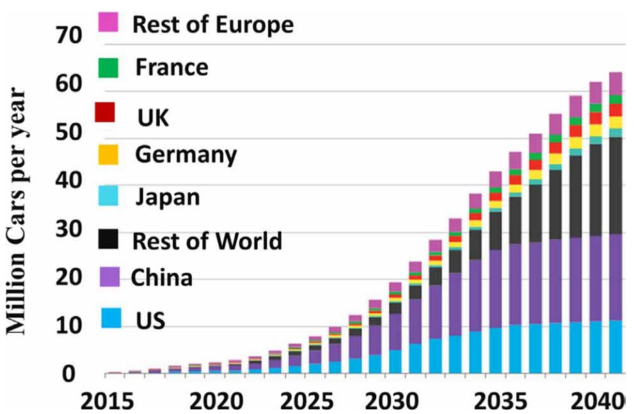

Fig. 23 Global EV evolution forecast. Figure has been reproduced from ref. 260 with permission from IGI global scientific publishing, copyright 2019.

energy release diagram also shows where the heat from internal short circuits (ISC) or combustion is released, although the displays for these chemical reactions are different. The separator's collapse temperature and the ISC's onset temperature are closely connected. For the polyethylene (PE) separator, the ISC can happen at around 130 °C, for the polypropylene (PP) or PP/PE/PP separator at 170 °C, and for the ceramic-coated separator around 200 °C.[124] Herein, the first breakdown of SEI is thought to be the first side reaction that happens during the entire thermal runaway process. The early disintegration of SEI takes place between 80 and 120 °C, with a peak at about 100 °C.[128,129] Once the SEI decomposes at a high temperature, the intercalated lithium-ions in the graphite anode can come into contact with the electrolyte. This leads a greater surface reaction between the lithiated graphite and organic compounds/transition metals/acidic attack, forming a new SEI.[129] Thus, due to the nature of electrolytes, a series of undesirable reactions between electrodes and electrolyte are immensely detrimental to thermal runaway. In particular, the electrolytes consist of a blend of different carbonates and are primarily composed of flammable linear carbonates such as combinations of diethyl carbonate (DEC), dimethyl carbonate (DMC), ethyl methyl carbonate (EMC), and ethylene carbonate (EC). Although linear carbonates provide high ionic conductivity, decreasing the electrolyte viscosity corresponds to better ion uptake into the polyolefin-based separator and creating a stable solid electrolyte interface layer on the graphite electrode surface.[130] Their low flash points lead to a higher combustion speed and heat release rate. Additionally, the addition of lithium salt does not greatly change the mixture's flash point, even while it lowers the vapor pressure and affects the period of combustion. The exposure of lithium-ion batteries to air during the thermal runaway process can result in dangerous flammability and toxic gas release.

In detail, the tracking and control of thermal runaway require a deep understanding of the mechanism as well as the physical and chemical processes during the four stages. Recently, X. Feng *et al.* provided a time sequence map (TSM) to point out the detailed thermal runaway mechanism for LIBs.[132] The idea of a thermodynamic system aids in classifying various physical and chemical processes in terms of the places in which they take place. The two-path pattern in Fig. 12 may be used to redraft the TSM since the physical and/or chemical processes can take place both within and outside the battery cell.[131] The

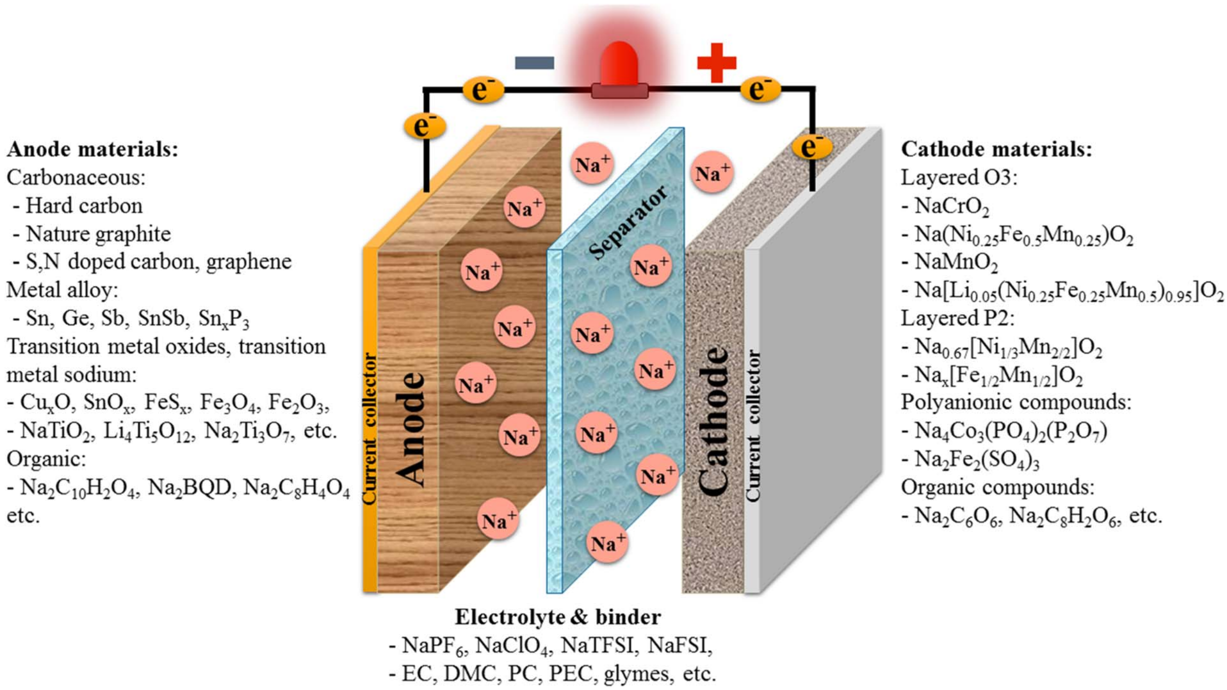

Fig. 24 General construction of one sodium-ion battery cell with intensively studied materials.

two-path pattern for deciphering the thermal runaway process of LIBs is shown in Fig. 12a. The OUT path symbolizes the smoke, fire, or explosion that occurs outside the cell, parallel to the IN path, which represents the heat failure caused by chemical reactions inside the cell. Fig. 12b shows more detail of the two-path pattern based on characteristic temperature and thermal-physical temperature. Up to thermal runaway, the IN route depicts the evolution of thermal failure within the cell case. The sequence of vent, smoke, and fire seen outside the cell case is depicted in the OUT route and is explained by the fire triangle. In summary, a time sequence map-based thermal runaway mechanism will show both specific internal triggers

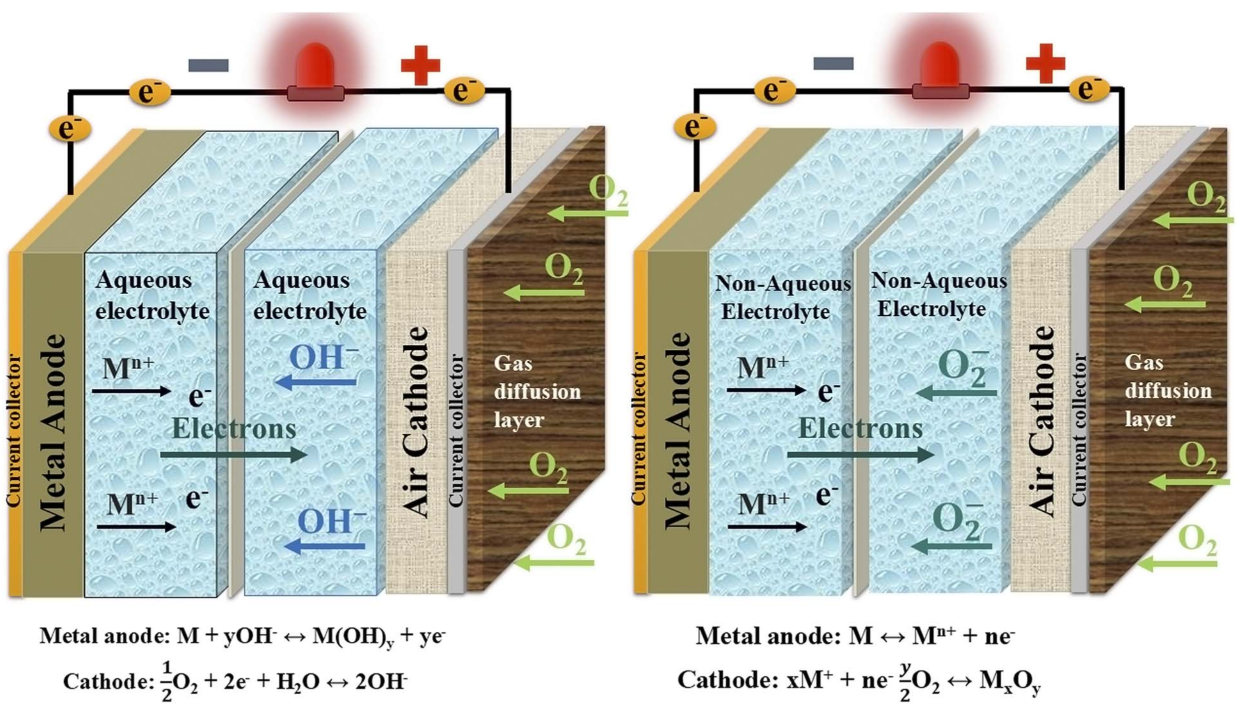

Fig. 25 Structure and working principle of aqueous metal–air batteries and non-aqueous metal–air batteries.

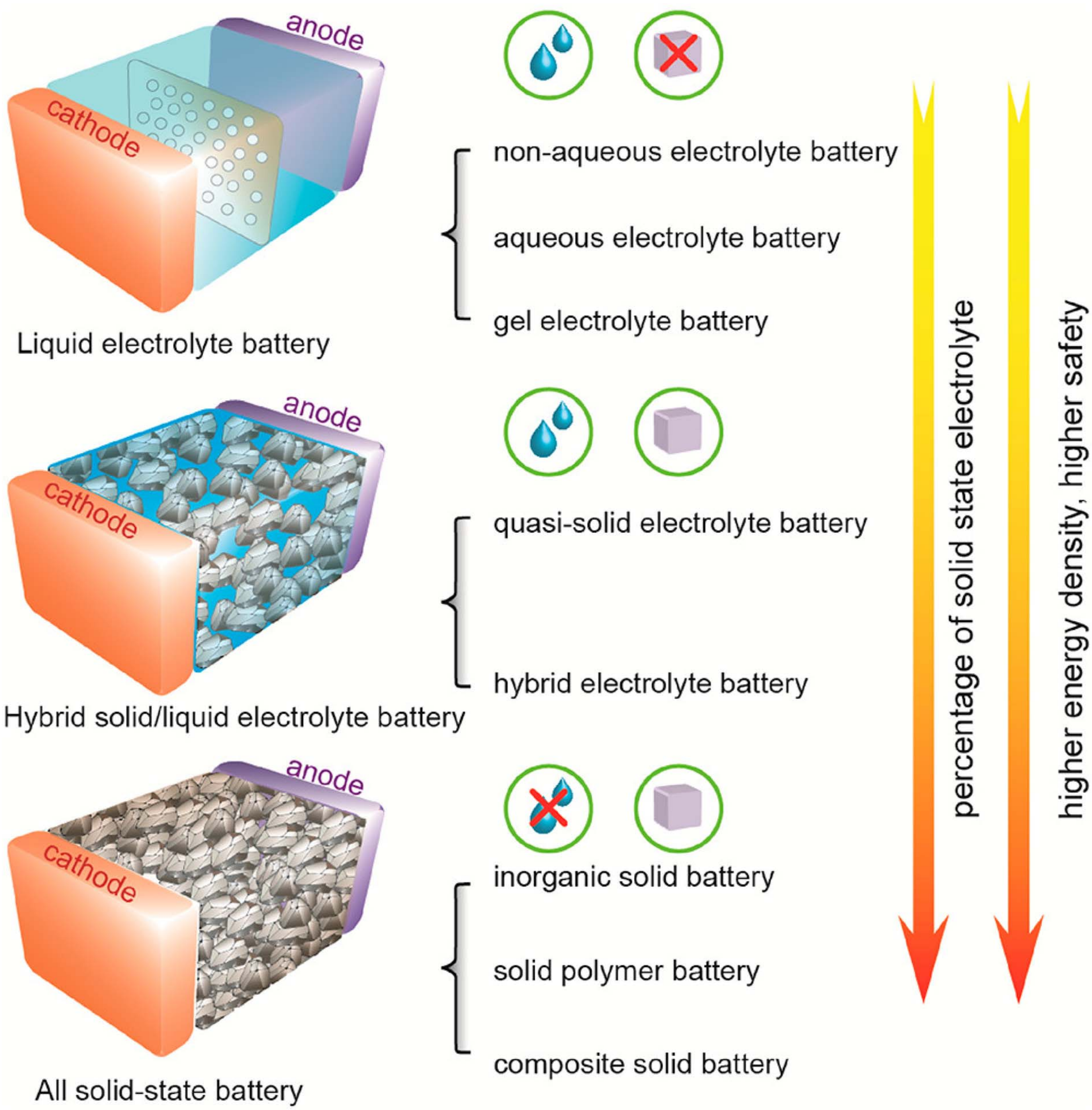

Fig. 26 Typical lithium-ion battery categories are shown schematically. Based on the volume of liquid and percentage of SSE in the built batteries, three different types of batteries may be identified. Figure has been reproduced from ref. 270 with permission of America Chemical Society, copyright 2020.

and events occurring outside the battery cell. Numerous studies concentrate on early warning of the thermal runaway threat to increase the safety of LIBs. The following categories can be used to categorize the monitoring techniques: (i) abnormal phenomenon monitoring of batteries in the early stage of thermal runaway, such as characterizing gas generation and internal/external force; (ii) early warning based on battery internal electrical characteristics; and (iii) temperature monitoring *via* the battery management system (BMS).[123,133,134] A combination method with external characteristics (voltage, current, temperature, and capacity) and internal mechanisms (electrochemical reaction and degradation of the material) should be developed for evaluating the electrochemical-thermal coupling properties of LIBs during the evolution of the thermal runaway phenomenon in order to establish an accurate and widely applicable thermal runaway prediction and early warning method. Additionally, in order to obtain a quantitative evaluation and forecast of the thermal runaway risk of LIBs, safety limits should be built based on electrochemical characteristics.

Actually, during the thermal runaway phenomenon, the creation and conversion processes between the solid, liquid, and gas phases combine to cause the gas venting of lithium-ion battery cells. This is really the outcome of both chemical

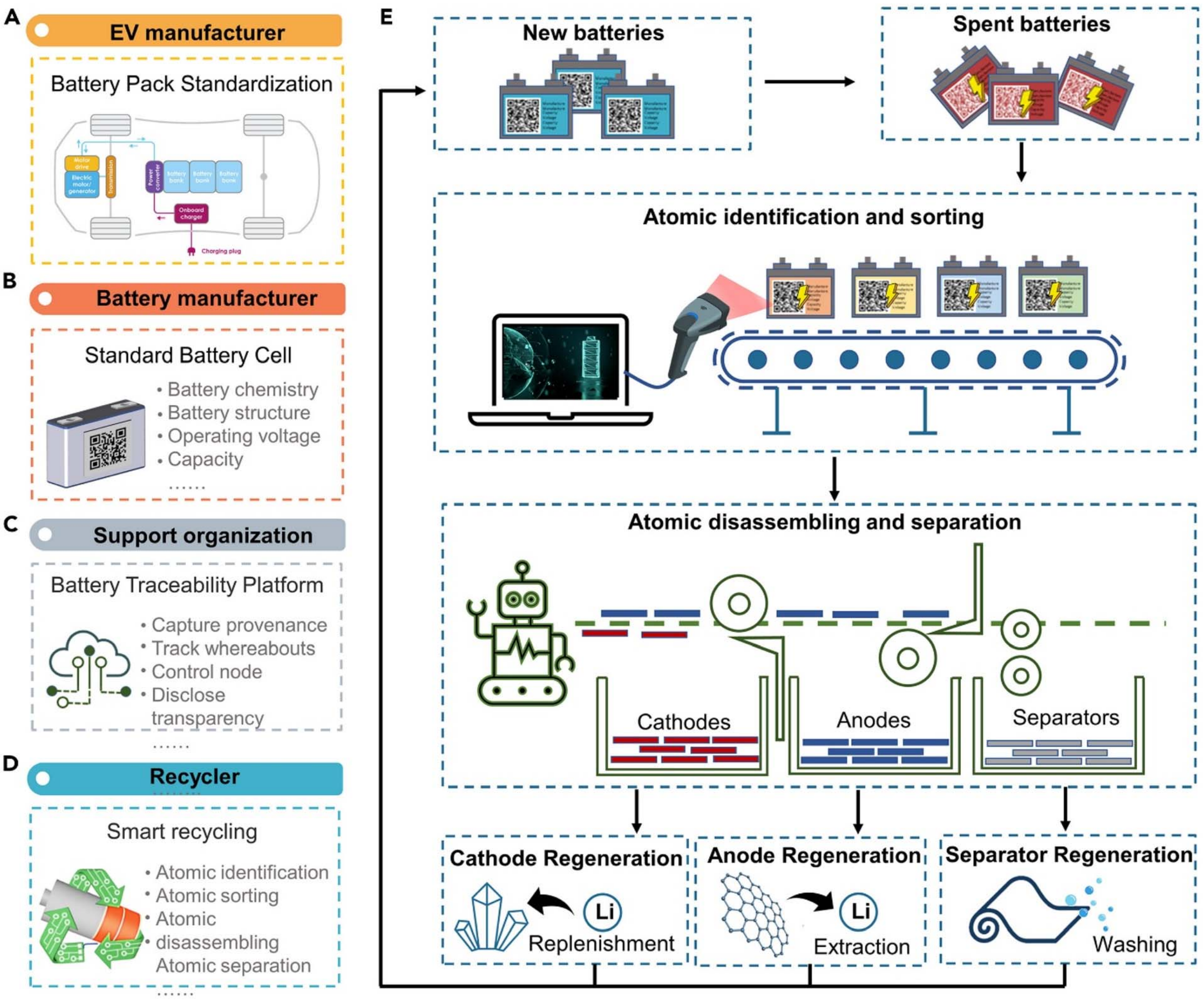

Fig. 27 The ideas toward a circularity for electric vehicle battery packs: (A and B) electric vehicle battery manufacturing and assembly, (C) settings to support and manage battery packs in real time during use, and (D and E) smart and closed-loop recycling processes using AI and robots. Figure has been reproduced from ref. 286 with permission from Elsevier, copyright 2023.

reactions and physical transformations. In response to inquiries regarding the reasons behind the jet flow's accompanying droplet and particle emissions during gas venting and the changes that battery materials suffer under thermal abuse, Wang *et al.* presented a model that demonstrates the transition process and mechanism for different stages during thermal runaway.[135] The following three regions, which correspond to different processes, are depicted in Fig. 13a: region 1 is the jelly roll, region 2 is the phase interface and headspace, and region 3 is the ambient fluid.[135–140] Moreover, apart from the produced gases and electrolyte vapors, a significant emission component of thermal runaway processes is the solid particle. Fig. 13b reports a schematic picture based on X-ray imaging of the thermal runaway cell, which explains how components of the electrode material are expelled from the jelly roll and are subsequently discharged as particles, which is depicted by four consecutive steps to the entire process.[135,139,141,142]

Recently, J. Kim *et al.* provided a detailed thermal runaway phenomenon of an 18 650 lithium-ion battery cell under the temperature evolution process (Fig. 14).[143] To investigate the cell venting, internal pressure, and gas-phase dynamics behavior of 18 650 Li-ion cells experiencing thermal runaway, a computational model is created. The turbulent flow out of the cells is characterized by a k-ε Reynolds-averaged Navier–Stokes model, while the fluid dynamics inside the cells are described by Darcy–Forchheimer's equation. A single-step lumped reaction model describes the kinetics of gas production and thermal abuse reactions. Then, a sequence of computational fluid dynamics simulations is carried out on a solitary 18 650 cell at different levels of charge at 100%, 50%, and 25% in order to examine intricate flow and temperature characteristics in relation to the amount of gas produced during cell venting. It has been discovered that the second stage dominates the cell response because thermal runaway produces the majority of the gases. State-of-the-art technology also has a big impact on the tendency for propagation. Due to larger reacting gas masses and concentrations, cells with higher state charges generate more heat and gas during the venting event. As a result, interior cell pressures rise, raising the possibility of sidewall breaching.

Recent advancements in thermal runaway early warning have shifted toward monitoring external characteristics that precede catastrophic failure, enabling timely intervention. Novel warning and assessment features, including force, gas, sound, optical signals, and impedance changes which have emerged as critical indicators.[144,145] For instance, gas sensors identify volatile organic compounds (*e.g.*, CO, CO_2, HF, CH_4) released during early-stage thermal runaway.[146–148] Acoustic emission techniques capture ultrasonic waves generated by microstructural damage, such as separator cracking or electrode delamination.[134,149,150] Optical methods, including infrared thermography and fiber optic sensor, provide real-time temperature and strain mapping with high spatial resolution.[151–154] Additionally, impedance spectroscopy tracks abrupt changes in internal resistance due to solid-electrolyte interphase (SEI) breakdown or short-circuit formation.[155–158] By integrating these multi-modal signals with machine learning algorithms, modern battery management systems (BMS) can achieve early thermal runaway prediction with over 90% accuracy, significantly improving safety margins for lithium-ion batteries in electric vehicles and energy storage systems.[159,160]

The rapid growth of EVs has been accompanied by a growing number of high-profile fire incidents, highlighting critical safety challenges in lithium-ion battery systems. Studies of these incidents demonstrate that thermal runaway often initiates at localized hotspots, frequently near cell edges in pouch cells, welding points, or overcharge/discharge within single cells, where microscopic defects (internal short circuits, dendrites, and electrode misalignment) create high-resistance zones.[113,121,161] Once triggered, exothermic reactions decompose the electrolyte and cathode materials, accelerating temperatures to 800 °C within seconds. Compounding these risks, thermal runaway from pack-to-pack propagation is spread by insufficient thermal barriers, leading to fire in the battery module. These real failures show a critical gap between standardized lab tests such as nail penetration and actual accident conditions, where multi-factors, including vibration, weather, high SoC, aging, parking space, and geography, interact unpredictably.[162–166]

2.5 Recycling lithium-ion batteries from electric vehicles

Another critical factor for the widespread adoption of EVs is establishing a circular material economy to ensure that waste from spent lithium-ion batteries does not undermine the environmental benefits. Recycling electric vehicle batteries is not a simple goal and requires managing the entire life cycle, which means coordinating from production and operational management to collection and recycling after use. In fact, lithium-ion batteries used for electric vehicles are very diverse in type, configuration, and generation. Each type of battery has specific requirements and characteristics related to the recycling process, along with strict regulations aimed at maximizing the use of recycled materials and ensuring high standards of environmental protection. In this section, the most general overview is provided to introduce the most realistic and concise view possible to help readers gain certain knowledge and identify current trends.

2.5.1 Lifetime prediction of lithium-ion batteries. Understanding the life cycle of lithium-ion batteries is essential to maximizing their lifespan and ensuring optimal performance. Thus, determining the life cycle of a lithium battery will help in deciding replacement time as well as dismantling leads to recycling.[167,168] When compared to the rate of product capacity, the actual capacity of lithium-ion batteries will continue to decrease after usage. A shift in this lithium-ion battery balance might result from any adverse events that could deplete lithium ions. This balance shift is permanent and can build up over many cycles of charge–discharge, which will negatively impact battery performance. Typically, a one-time battery charge and discharge is one cycle, and the cycle life is an important index to evaluate the battery life performance. The fundamental reason behind the factors affecting the life cycle of lithium-ion batteries is that the number of lithium ions participating in the energy transfer process is continuously decreasing.[169–171] Here, the total amount of lithium in the battery has no change, but the activated lithium ions decrease because they are trapped in some places or the transmission channel is blocked, causing by various reason, such as working temperature fluctuations,[172–178] charge/discharge aging,[179–181] solid electrolyte interphase (SEI) and dendrite growth[182–186] formation makes these ions unable to freely participate in the charging and discharging process. Therefore, monitoring information about the performance of each battery cell and the entire battery cell and battery module will help determine the battery life cycle to meet the capacity requirements of the battery module and determine when to remove it for recycling. Recently, Wang *et al.* introduced s consistency prediction based on actually operating data.[187] In their report, the ohmic internal resistance, electrochemical polarization internal resistance, and concentration difference polarization internal resistance were determined to be the characteristic parameters from the electric vehicle operation data using the recursive least squares with forgetting factor algorithm for the second-order equivalent circuit model parameter identification. Second, a time series prediction model and a thorough battery pack inconsistency assessment model are put forward, both of which are capable of precisely assessing and forecasting battery pack inconsistencies. Lastly, nine months of real electric vehicle usage data are used to evaluate the system. The findings demonstrate the high accuracy of the suggested inconsistency evaluation and prediction approach. The general process is showed in Fig. 15.[187] In general, predicting the remaining operating time of the battery module is very important to help regulate as well as ensure safety during operation. Moreover, this will help the process of replacing old batteries and putting them into the recycling process.

Accurate state-of-charge (SOC) estimation is crucial in determining the remaining energy capacity of LiBs before they enter the recycling process.[188] SOC reflects the available charge relative to the maximum capacity of battery, providing insights into its usability, degradation level, and potential for battery second-life applications.[188–190] For recycling decisions, evaluating the SOC helps assess whether a battery has reached its end-of-life or still retains sufficient capacity for repurposing in less demanding applications, such as energy storage systems.[191–193] Batteries with high residual capacity may be diverted to secondary markets, reducing waste and improving resource efficiency, while deeply degraded cells with low SOC are more likely to undergo material recovery *via* recycling process. Thus, SOC estimation serves as a key parameter in the decision-making process, ensuring economically and environmentally optimized battery disposal or reuse. The importance of SOC estimation extends beyond operational performance which can play a pivotal role in sustainable battery lifecycle management. Precise SOC assessment prevents premature recycling of batteries that could still deliver value in secondary applications, thereby extending their service life and reducing environmental impact.[194] Additionally, knowing the exact SOC ensures safe handling during recycling, as partially charged batteries may pose thermal runaway risks if improperly dismantled. From a resource recovery perspective, SOC data aids recyclers in optimizing processes such as discharge protocols and material extraction, improving efficiency and cost-effectiveness.[195] With the strong growing of EVs, integrating reliable SOC estimation methods into recycling frameworks will be essential for maximizing resource utilization and advancing circular economy principles in the LiB industry.[194–197] There are many studies on SOC to provide the most optimal and complete solutions with the ambition to optimize battery performance and help improve durability. To enhance the accuracy and robustness of state-of-charge (SOC) estimation in lithium-ion batteries (LiBs), Shi *et al.* proposed an Improved Adaptive Square Root Cubature Kalman Filter (IASRCKF) method, which dynamically adjusts the window length of noise statistics based on error innovation sequences.[198] The study first identified battery model parameters using an Adaptive Forgetting Factor Bias Compensation Recursive Least Squares (AFFBCRLS) method (Fig. 16a), achieving a voltage estimation RMSE of 0.004 V. The IASRCKF demonstrated superior performance over conventional ASRCKF, reducing SOC estimation errors to 0.18% RMSE and 0.15% MAE while maintaining rapid convergence under varying initial SOC and noise conditions (Fig. 16b). Despite its high accuracy, the method's reliance on empirical parameter tuning and computationally intensive matrix operations may limit its practicality for low-cost hardware. The authors suggest future work on parameter optimization and aging-aware algorithms to improve efficiency and applicability. This work highlights the potential of adaptive filtering techniques for precise SOC estimation, which is critical for battery health assessment prior to recycling decisions.

Recently, Wang *et al.* presented a hybrid Radial Basis Correction-Differential Support Vector Machine (RBC-DSVM) model combined with a Limited Memory Recursive Least Squares (LMRLS) algorithm to achieve high-precision SOC estimation for LiBs in urban electric vehicles.[199] The study addresses the challenges of nonlinear SOC dynamics and time-varying battery parameters by integrating three key innovations: (i) an LMRLS-based online parameter identification method for the first-order Thevenin equivalent circuit model (FOT-ECM), which adaptively tracks ohmic resistance (R_0), polarization resistance (R_P), and capacitance (C_P) with a maximum voltage error of 0.064 V—outperforming conventional RLS in dynamic conditions (Fig. 17a); (ii) an adaptive RBC-DSVM model that iteratively corrects SOC errors by fusing Ah integration and AEKF inputs, leveraging a radial basis kernel function to map nonlinear relationships between voltage, current, and SOC (Fig. 17b); (iii) experimental validation under Hybrid Pulse Power Characterization (HPPC) and Dynamic Stress Test (DST) conditions, demonstrating remarkable accuracy with maximum SOC errors of 0.037% (HPPC) and 0.336% (DST), representing 89.78% and 6.15% improvements over AEKF, respectively. The RBC-DSVM's robustness is further evidenced by its stable error convergence under varying initial SOC values and measurement noise. However, the authors note limitations, including computational complexity due to matrix operations, empirical tuning of hyperparameters (*e.g.*, memory length *L*), and unvalidated performance under real-world noise and temperature fluctuations. Future work aims to optimize computational efficiency and incorporate aging effects. This study advances BMS technologies by bridging model-driven and data-driven approaches, offering a scalable framework for real-time SOC estimation in EV applications.

In summary, the modern SOC estimation methods leverage advanced algorithms, such as adaptive Kalman filters, machine learning models, and hybrid data-driven approaches, to address challenges like nonlinear battery dynamics, noise interference, and real-time computational constraints. However, challenges remain in computational efficiency, real-world noise resilience, and aging-aware modeling. Future advancements aim to integrate these techniques with battery recycling frameworks, ensuring accurate SOC assessment for end-of-life repurposing or material recovery, thereby supporting a sustainable EV ecosystem.

2.5.2 Battery recycling technologies. The issue of recycling or replacing LIBs with the next generation has drawn considerable attention from the general public and governments due to the fact that LIBs have grown to be so popular due to their enormous benefits and difficulty in replacement. Lithium, cobalt, nickel, manganese, and other metals have finite and unequally distributed global deposits, and their extraction requires a lot of energy and labor and causes a lot of pollution (Fig. 18).[200,201] Moreover, the size of the battery and the power source used for charging have an impact on the environmental performance of battery-electric cars.[202] As a result, modifications to the electrical industry and battery refurbishment should be taken into account when evaluating their environmental performance. For electric cars and renewable energy storage systems, lithium-ion batteries have emerged as a critical link in the energy supply chain.[203] Recycling is regarded as one of the best methods for recovering materials from used LIB streams and redistributing them throughout the supply chain.[204]

In fact, removing batteries from a device might generate a significant amount of waste for the environment. In addition, batteries contain a lot of dangerous elements, making it unwise to discard them directly. Addressing this, battery recycling is the technique of reusing and processing batteries with the intention of lowering the amount of batteries disposed of as material waste.[205] Batteries include a number of toxic compounds and heavy metals, and the pollution of land and water caused by their disposal has raised environmental concerns.[206] Currently, in order to guarantee the highest level of safety throughout the transport process, the problem of shipping chemicals for battery manufacture as well as released batteries must meet several stringent and challenging standards. Nowadays, most production materials, including spent cells for recycling as well as commercial cells, are frequently transported by container ships across the ocean due to their low cost, high transport capacity, superior safety compared to airplanes, and ease of movement between continents. Recycling battery is necessary for both environmental and health reasons. Lithium-ion batteries must be disassembled and separated due to their complicated structure and several distinct material types before applying recycling techniques such as pyrometallurgy, hydrometallurgy, direct recycling, and combination procedures (Fig. 19).[207–209]

For improved resource recovery and an energy-efficient recycling procedure, particularly in the case of hydrometallurgy and direct recycling pathways, wasted LIBs must be physically and chemically pre-treated and separated.[210] The procedure is also necessary for recovering valuable materials like Ni, Co, and Li as well as less valuable elements (also known as impurity elements), such as Al, Fe, Cu, and C.[211] Discharging, disassembling, separating, dissolving, and thermal treatment are only a few of the pre-treatment process's sequences, according to numerous phases and procedures that have been classified as part of the pre-treatment process.[212] Pre-treatment procedures are often described as those that include classifying and separating different LIB components and elements in order to make future recycling procedures more effective and less impurity-intensive.[213,214]

Pyrometallurgical technology is a convenient strategy that can convert metal oxides to metal compounds or pure metal by using heating and melting processes.[215–217] After pretreatment, the battery materials are heated in reductive roasting (smelting) to change the metal oxides into a mixed metal alloy that may contain cobalt, nickel, copper, iron, and slag containing lithium and aluminum, depending on the battery composition. The crushed wastes are melted in a furnace or molten bath during the pyrometallurgy process to extract polymers. The main drawbacks of pyrometallurgical processes are high investment costs, high energy requirements, and the discharge of hazardous gases into the environment, despite the fact that they are claimed to be economically effective and fully utilize the recovery of a sufficient number of precious metals.[218,219]

Hydrometallurgical technology generally employs aqueous solutions in order to extract and isolate metals from LIBs.[220] In this method, various types of acids such as HCl, HNO_3, H_2SO_4, and organic acids like citric, oxalic, and ascorbic acid are frequently employed, which are used to extract the pretreatment battery components.[221,222] Then specific metals are selectively precipitated as salts using pH variation after they have been extracted into solution, or they are extracted using organic solvents that include extractants.

Direct recycling, one of the most innovative and promising new LIB recycling techniques now under development, has started to be applied commercially.[223] In actuality, not every component of a battery needs to be recycled; certain components need to be replaced while others are still functional, such as removing and recycling the cathode while other parts are taken out and utilized again.[224–227] Therefore, for the goal of replacing and recycling damaged parts, the direct recycling approach presents a sensible and economical strategy.[228] Maintaining the purity of the material waste streams, which necessitates specialized processing for cell packing and component removal, is one of the most crucial aspects of direct recycling.[229]

Due to the unique benefits and drawbacks of each technique (Table 2), combinations of hydrometallurgical and pyrometallurgical processes are often utilized to produce lithium-ion batteries today. Pyrometallurgical techniques are probably utilized because they give battery materials diversity and because they require fixed investment in already-existing facilities. On the other hand, methods that are still being developed rely more heavily on hydrometallurgy due to its cost-effectiveness. In reality, the classification of the above technologies is only relative when studies have shown that a harmonious combination of the above methods will have the best effect. Therefore, for each type of lithium-ion battery and for each recycling purpose, the above methods will be calculated in detail and combined to form the most optimal process possible.

The recycling of spent EV lithium-ion batteries is being revolutionized by emerging technologies that address the limitations of conventional pyrometallurgical and hydrometallurgical methods. Direct recycling employs low-energy processes such as electrochemical relithiation and solvent-assisted separation to restore degraded cathodes (*e.g.*, NMC, LFP) to their original state, preserving >95% of their structure while reducing energy use by 50–70% compared to smelting (Fig. 20).[230–232] Meanwhile, bioleaching leverages bacteria (*e.g.*, Acidophilic microorganisms, Bacillus foraminis, A. ferrooxidans, Gluconobacter oxydans) to selectively extract metals like cobalt and lithium under mild conditions, minimizing toxic chemical waste and operating costs.[233–236] For binder and electrolyte removal, supercritical CO_2 extraction offers a green alternative to incineration, dissolving PVDF and organic solvents without emissions.[237,238] Advanced sorting technologies, including AI-driven robotic disassembly and laser-induced breakdown spectroscopy (LIBS), enable precise separation of battery components by chemistry, critical for handling diverse EV battery designs. However, challenges persist in scaling these technologies such as bioleaching remains slow (days *vs.* hours for acid leaching), and direct recycling struggles with contaminated or mixed feedstocks. Innovations like plasma-assisted pyrolysis for binder removal and closed-loop solvent recovery systems are under development to improve efficiency.[239,240] With the EV market projected to generate more than 11 million tons of battery waste annually by 2030,[241] these technologies which backed by policies like the EU Battery Regulation, could transform recycling into a high-yield, low-carbon industry, recovering more than 90% of critical materials while meeting stringent sustainability targets.

2.5.3 A circular economy in the context of electric vehicle battery recycling. The circular economy is an economic model in which products, materials and resources are kept in the economy for as long as possible, through activities such as reuse, repair, recycling and waste reduction.[242–244] The goal of the circular economy is to reduce dependence on natural resources and reduce waste and environmental pollution. Battery recycling is an important part of the circular economy, especially in the context of the increasing use of lithium batteries in electric vehicles, because spent lithium batteries contain many valuable materials, such as lithium, nickel, and cobalt, which can be recovered and recycled to produce new batteries or other products, reducing the need to mine new resources (Fig. 21).[245]

A circular economy model prioritizes three key phases: (i) reuse of spent battery packs from EVs through second-life applications like stationary energy storage, (ii) building a standard battery collection system for all types of batteries from small electronic devices to electric vehicles, and (iii) recycling for recovering critical materials *via* pyrometallurgical, hydrometallurgical, or direct recycling methods.[245–249] Advanced recycling techniques, such as hydrometallurgy with solvent extraction or electrochemical leaching, can recover high-purity metals, drastically reducing the requirement for virgin mining. However, challenges still persist, including the economic viability of recycling technologies. Recent emerging innovations, such as AI and robotic disassembly systems, promise to enhance recycling efficiency. By closing the loop on battery materials, a circular economy purpose not only mitigates environmental risks and reduces ore mining but also improves the living environment and raises public awareness of environmental protection and sustainable development toward achieving zero tailpipe emissions.

2.6 Future outlook of electric vehicles

2.6.1 Current issues. The next decade will see the explosive growth of EVs of different sizes and the expansion of different types of batteries, mainly lithium batteries. In fact, emissions from traditional vehicles using fossil fuels are harmful to both human health and the environment, such as asthma, bronchitis, cancer, and early mortality, which are all caused by the air pollutants released by gasoline and diesel-powered vehicles.[250] By offering a fresh turn in technology, the introduction of electric cars may assist in lessening the issue with traditional vehicles.

The rapid growth of EVs over the coming decade will undoubtedly place heavy demands on electrical infrastructure. The daily power consumption will be enormous, and the power transmission infrastructure will also need to be improved to supply charging stations that are dispersed over a wide region.[251] As a result, the power generation system will be under a lot of strain, raising the important issue of how enough electricity will be generated to satisfy this demand.[252,253] The two primary sources of energy used today are hydroelectricity and coal-fired thermal power; however, coal-fired thermal power requires fossil fuels like coal, which contradicts the goal of reducing CO_2 emissions. As a result, it is important to develop renewable energy sources like solar and wind power in concert with the existing infrastructure (Fig. 22).

The chance to replace fossil fuels in the transportation industry is provided by electric automobiles. Increased energy efficiency, less air pollution, and a decrease in global warming can all be advantages of electrifying the transportation industry. Yet, there are legitimate worries about how to meet the future energy demand for recharging the batteries of electric vehicles with clean and renewable sources. The concerns associated with the availability of the precursor materials required to make electric car batteries serve as a further reminder of the problem of the long-term viability of EVs. Some of these material resources' exploitation is associated with serious environmental, ethical, and societal problems.

Moreover, one major emergency situation for all types of electrical vehicles is the recycling problem of spent batteries, which are discharged into the environment every year. The requirement to recycle spent electric car batteries can be considered an extremely urgent and important request in the context of increasing pollution of water and air and global warming. As well, a significant number of precursor materials for the manufacturing of electrodes, such as lithium, cobalt, manganese, and nickel, will be required due to the enormous demand for batteries for the electric car revolution in the coming decade. Not only does this endanger the ecosystem, but it also depletes mineral supplies. As a result, better technologies must be created in order to properly recycle spent batteries.

Currently, 50 percent of the world's EV market is now made up of all-electric cars (BEVs). Sales of BEVs are increasing more quickly than those of plug-in hybrid electric vehicles (PHEVs).[254] But various markets have very varying preferences for powertrains, which are determined by legislative measures, consumer preferences, and the availability of certain models. Following the various databases of the global market for electric vehicles, a market overview is given by us based on detailed and verifiable statistics from the data collected and presented below.[255–259] Fig. 23 shows the global forecast sale of electric vehicles with two biggest markets for electric vehicles in the world, China and North America, continue to offer buyers a wide range of options.[260] In the foreseeable future, Europe is starting to emerge as a significant market. Both the further integration of renewable energy and the growing number of electric cars will have a significant impact on the future transformation of the European electrical grid.[261] Rest of world, especially India will become the biggest population in the world and is the most attractive market in Asia after China, but it has significant infrastructural challenges that will take 10 to 20 years to resolve.[260,262] Japan will be fierce competition from electric vehicle manufacturers due to the rather strict requirements of consumers in these two countries; moreover, the industrial science and infrastructure are very developed. Southeast Asia, although still underdeveloped, has seen strong economic growth in the past two decades and promises to be a dynamic economic region and a fertile ground for electric vehicle manufacturers.[263] Overall, China will continue to lead the world in producing electric car batteries over the next ten years, and it will do so with undeniable advantages. In order to jointly develop and build a large number of EVs, many multinational automakers established brand-new joint ventures with local Chinese factories.

2.6.2 Future perspectives and challenges of next-generation batteries for EVs. Because of their high energy and power densities, reliability, and longevity, LIBs have proven to be efficient energy storage devices. However, LIBs confront several safety and explosive issues in addition to significant difficulties with the precious metal resources utilized as electrodes, such as lithium, nickel, cobalt, *etc.* Additionally, the capacity of the recycling sector is still insufficient to satisfy the demand to recycle all used LIBs. Finding the next generation of batteries that can get around these drawbacks is therefore critically needed. Under such circumstances, a number of candidates—including sodium-ion batteries, metal–air batteries, and all solid-state lithium batteries—emerge as deserving replacements.

Sodium-ion batteries are a kind of rechargeable battery that works like lithium-ion batteries but uses sodium instead of lithium electrodes as well as a sodium electrolyte (Fig. 24). Sodium-ion batteries could dominate the global battery market in the future due to their low cost and plentiful supply of sodium resources and promising large-scale production, which makes them less expensive per kilowatt-hour.[264] Recently, some studies have focused on using hard-carbon anodes for sodium-ion batteries due to their low cost, available sources, and stable structure. Hard-carbon materials have a porous structure that allows sodium ions to easily move and store during charging and discharging, resulting in high energy density and good stability.[265] Therefore, hard carbon is considered a highly commercial material for sodium-ion batteries. Sodium-ion batteries leverage abundant, low-cost sodium resources, reducing geopolitical risks associated with lithium, while maintaining similar intercalation chemistry, enabling compatibility with existing manufacturing infrastructure; however, their lower energy density and larger Na^+ ionic radius, which slows diffusion kinetics and degrades cycle life, limit widespread adoption.

Metal–air batteries are like lithium-ion batteries, and both are types of rechargeable batteries. As shown in Fig. 25, metal–air batteries use an external cathode (positive electrode) that reacts with oxygen from the air, facilitated by carbon and specific metals, while the anode (negative electrode) can be made from metals such as zinc, aluminum, magnesium, or lithium.[266] According to theoretical calculations, metal–air batteries have an energy density many times higher than lithium-ion batteries, which gives hope for a future generation of rechargeable batteries that can be widely used in energy storage industrial systems and opens up great prospects for electric cars.[267] Metal–air batteries boast ultrahigh theoretical energy densities, making them ideal for electric vehicles, but suffer from poor rechargeability, electrolyte decomposition, and cathode clogging by discharge products (*e.g.*, Li_2O_2), necessitating advanced catalysts and stable electrolytes. In the detailed, metal–air batteries have a solid electrolyte interphase (SEI) film is a passivation layer that sits between the metal anode and the electrolyte. It is particularly challenging to prevent the crossover of the air constituents and the degradation of the SEI present on the metal anodes. Batteries also develop dendrites upon metal plating on the anode, which can cause a short circuit and an explosion. Another significant issue is the cathode material's poor resistance to degradation throughout the charge–discharge operation.[267–269]

All-solid-state lithium batteries (ASSLBs) are more viable alternatives to LIBs, offering higher energy density, improved safety, reliable high-temperature operation, and long-term durability, irrespective of their electrolyte type (solid polymer or inorganic) (Fig. 26).[270] The original purpose of solid-state batteries, which have recently attracted a lot of interest, was to enhance the practicality of electric vehicles. Due to their greater energy density and capacity to accommodate larger cells in the same space as lithium-ion batteries, ASSLBs may soon conquer the global market. The ASSLBs are now the subject of considerable study and testing on a very small scale in order to be produced in huge quantities in the future. The high interfacial resistance and lack of stability of solid–solid contact at the electrolyte/electrode interface is one of the obstacles that must be overcome in reality.[270–273] The stability and compatibility of the interfacial environment also have a significant impact on the electrochemical performance of batteries.[274] In summary, solid-state lithium batteries address safety concerns by replacing flammable liquid electrolytes with solid counterparts, enabling higher energy densities and dendrite suppression, yet face interfacial resistance issues, brittle electrolyte mechanical properties, and high production costs due to complex sintering processes.

The recycling of next-generation batteries presents significant challenges due to their diverse chemistries and structural complexities. Sodium-ion batteries, while sharing similar properties with lithium-ion systems, suffer from lower material value, making traditional pyrometallurgical or hydrometallurgical recycling economically unviable without government assistance.[275,276] Additionally, the prevalence of aluminum current collectors in both electrodes complicates separation processes. Metal–air batteries have some limitations of their open cathode structures, which absorb atmospheric CO_2 and moisture, leading to carbonate formation that contaminates recyclable components.[277–279] Solid-state lithium batteries require new recycling strategies, as their ceramic- or sulfide-based solid electrolytes are often brittle and intermixed with electrode layers, necessitating energy-intensive mechanical separation, and their stable inorganic components resist traditional leaching processes.[280–282] Furthermore, the lack of standardized designs across these emerging technologies hampers the development of universal recycling protocols, increasing costly and specific recycling strategies for each battery type. Overcoming these challenges requires advances in direct recycling methods, automated disassembly, and policy frameworks to incentivize recovery of low-value materials like sodium or complex solid electrolytes.

2.6.3 The recent emerging recycling technologies. The first half of the 2020s has witnessed the remarkable development of information technology, with the highlight being artificial intelligence (AI), which has been introduced and widely used in many fields, from industry to commerce and services.[283–285] Following this influence, AI has been integrated into electric vehicles for many different purposes, such as a virtual secretary to support drivers, intelligent autopilot mode, and battery management system. Currently, AI and robotic arms are being researched to integrate into the inspection and recycling stages of spent battery packs. AI can be used to diagnose the safety level and remaining energy status before automatically adjusting the line to the dismantling stage with robotic arms in a closed room environment to protect people from toxic chemicals and unexpected explosions.[286–289] Fig. 27 illustrates a recycling process for old EV battery packs that uses AI to identify their condition before moving on to dismantling and sorting components using a programmable robotic arm. Fig. 27a and b show the critical initial steps in developing the automation of the disassembly process, which is standardizing the manufacturing, size, form, and construction of battery packs and cells. The recycling of used LIBs also requires the establishment of a thorough BMS (Fig. 27c). Then, the AI and programmable robotic arms should concentrate on developing and implementing an automated recycling system that includes identification, sorting, disassembly, and separation according to the standardized standards (Fig. 27d). An intelligent procedure will be essential to the future of effective LIB recycling (Fig. 27e).

The direction of battery recycling technology in the near future is to incorporate AI and robots into the diagnostic phases of pre-recycling as well as the entire process of disassembly, separation, and refinement to recover the most precious metals possible in the form of metal salts, lithium salts, and pure foil. These new technologies will reduce the hazards of gas venting and chemical emissions during the disassembly and recycling process, as well as the explosion incidents and toxic exposures to humans. In addition, breakthrough technological improvements will also be applied to improve traditional recycling methods such as hydrometallurgy and pyrometallurgy to reduce process operating costs and increase output product quality.

3 Conclusions

This review comprehensively examines four commercial EV types (BEVs, HEVs, PHEVs, and FCEVs) with a focus on their LIB architectures and safety challenges, particularly thermal runaway risks. By synthesizing recent experimental studies, we demonstrate that thermal management systems (*e.g.*, liquid cooling, phase-change materials) and battery design modifications (*e.g.*, ceramic-coated separators, silicon anodes) significantly enhance safety but require further optimization for extreme conditions. Our analysis also reveals that while current recycling methods—pyrometallurgy (80–95% metal recovery), hydrometallurgy (high purity but energy-intensive), and direct recycling (cost-effective but scalability-limited)—address LIB waste, none yet offer a perfect solution for the impending surge of end-of-life EV batteries.

The transition to EVs is inevitable, driven by climate policies and technological advances. However, critical barriers persist, including: (1) charging infrastructure scalability, (2) renewable energy integration to ensure true decarbonization, and (3) sustainable, closed-loop battery recycling systems. Innovations like solid-state batteries and sodium-ion alternatives show promise but demand rigorous validation. This work not only consolidates current knowledge but also provides actionable insights for policymakers and researchers to accelerate EV adoption while mitigating environmental trade-offs. Future efforts must prioritize interdisciplinary collaboration to address these challenges holistically, ensuring EVs fulfill their potential as a sustainable alternative to ICE vehicles.

Author contributions

Phuoc-Anh Le: writing – review & editing, writing – original draft, validation, methodology, investigation, formal analysis, data curation, conceptualization.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships.

Data availability

No new data were generated or analyzed in this study. All data supporting the findings of this review are available within the manuscript and the references cited.

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