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# Development and Commercial Application of Lithium-Ion Batteries in Electric Vehicles: A Review

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**Abstract:** Lithium-ion batteries are one of the critical components in electric vehicles (EVs) and play an important role in green energy transportation. In this paper, lithium-ion batteries are reviewed from the perspective of battery materials, the characteristics of lithium-ion batteries with different cathode and anode mediums, and their commercial values in the field of electric vehicles. Representative products, including blade battery and Tesla 4680 cells, are inspected. Moreover, the results of commercial application of lithium-ion batteries in electric vehicles are summarized. Furthermore, cutting-edge technologies of lithium-ion batteries are discussed, including electrolyte technology, high-energy-density in situ polymerization technology, and pouch batteries. Finally, the latest EV battery technology development is looked over, including challenges and future development directions.

**Keywords:** electric vehicles; lithium-ion battery; development planning and applications

## 1. Introduction

Electric vehicles (EVs) are one of the most promising technologies for green transportation systems. To achieve zero carbon, many countries have introduced subsidies and particular tax policies for new energy vehicles, for instance, plug-in car subsidies in the United Kingdom, new energy car rebates in the United States, and pollution-free car purchases in Japan [1]. Furthermore, many countries have set timelines for the shift to new energy vehicles. For example, in Norway, all newly sold passenger cars and vans should be zero-emission cars by 2025. All new vehicles sold in China by 2035 must be powered by new energy sources [2].

New energy vehicles mainly include EVs, ethanol automobiles, hydrogen automobiles, methanol automobiles, and gas automobiles. Among them, EVs have advantages, such as no greenhouse gas emissions, easy maintenance, low noise, low operating costs, and renewable energy use. Therefore, EVs have a broad development prospect. Usually, EVs can be divided into battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs) [3,4]. The configurations of several types of EVs are shown in Figure 1.

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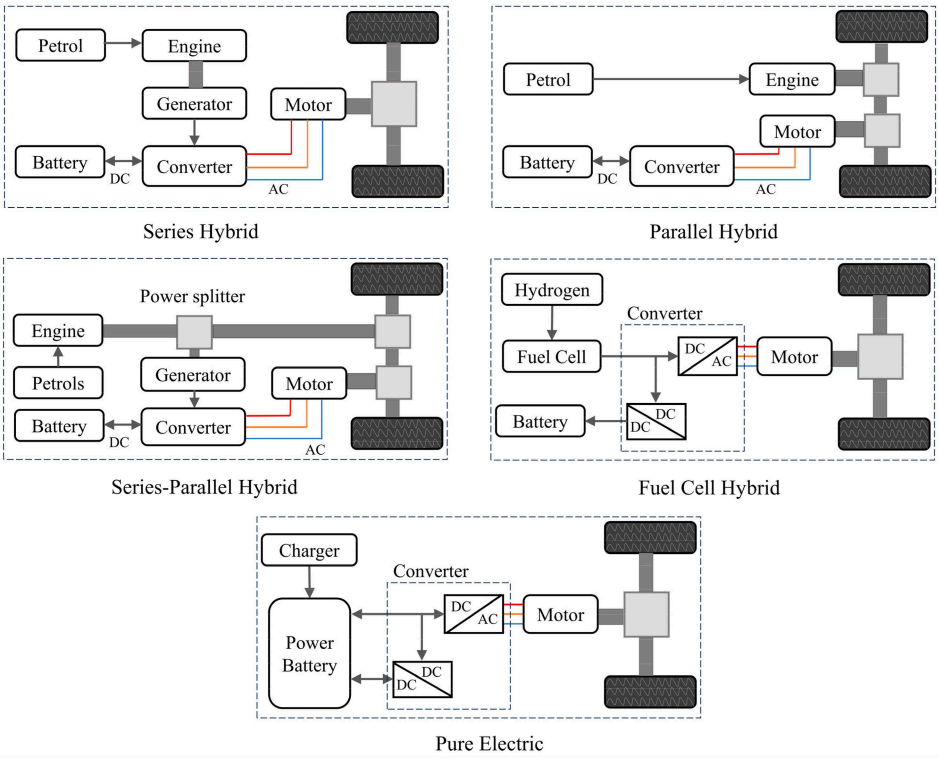
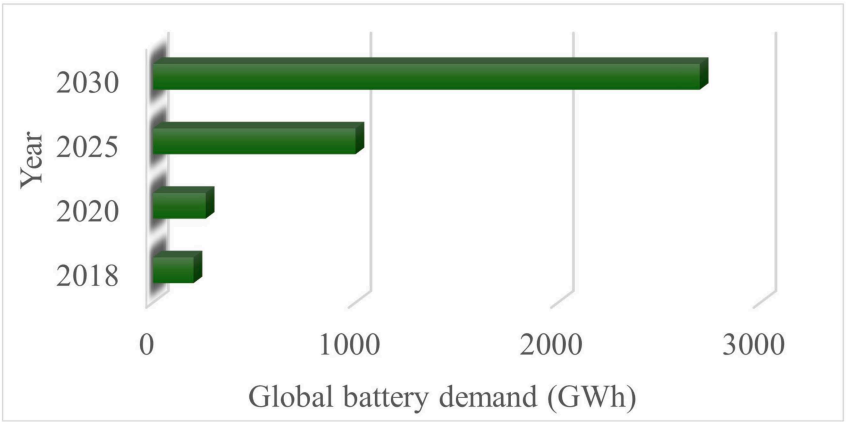



**Figure 1.** Architecture of various EVs configurations. Sourced from [5] and redrawn by the authors.

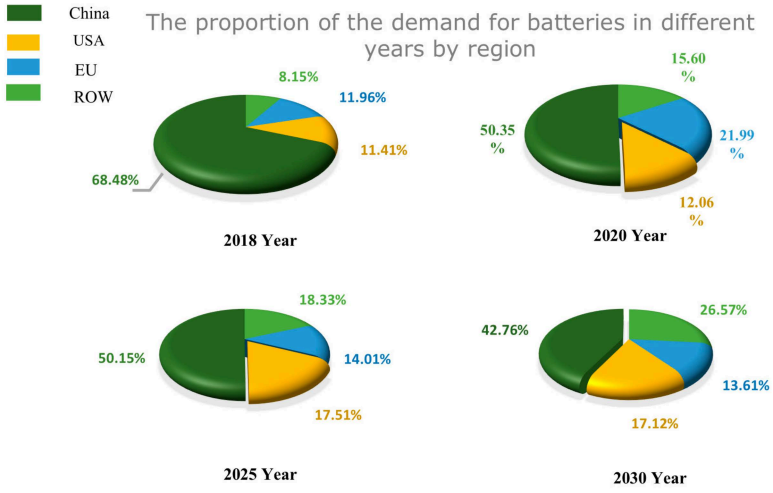
BEVs, called pure electric vehicles, are entirely powered by traction batteries [6]. HEVs' drive systems are composed of two or more single-drive strategies that can drive simultaneously. In FCEVs, a hydrogen fuel cell generates electricity to run the car. The fuel cell produces excess energy, stored in a storage system. An advantage of FCEVs is that they create their electricity without the emission of carbon monoxide—the by-products of their reaction results are mainly water, with a very small amount of carbon dioxide and nitrogen oxides. Consumers have recognized the advantages of EVs. In January 2017, HEVs and BEVs accounted for around 10% of car model manufacturing in the United States. In the same year, an estimated number was almost 695,000 EVs running on the roads worldwide [7,8]. Even with the impact of COVID-19, Europe added 200 GWh of the EV production capacity in 2020, and the total EV production capacity exceeded 600 GWh in 2021. Specific to European countries, the number of BEVs and PHEVs in Germany exceeded 1.1 million in 2022, an increase of 101% compared to the last year, and nearly 1.5 million by July 2022, an increase of 48% compared to January, which can almost double every year [9]. The Chinese market is even more dynamic, with more than 60% of EVs sales in 2018 taking place in China. Regarding growth, the number of light EVs in China increased from 220,000 in 2015 to 1,120,000 in 2018 [10].

The battery is one of the essential parts of EVs, which powers EVs directly. Figure 2 forecasts the growth and distribution of the global battery industry. The battery industry will maintain a high growth trend and exceed 2500 GWh in the next ten years. China accounts for a large proportion of the global battery demand, and the rest of the world (ROW) is expected to gradually increase its proportion, which indicates a growing emphasis on the battery industry in all regions of the world. Critical indicators for evaluating batteries include energy, power, safety, cost, and life [11]. Before the popularization of lithium batteries, people used two candidates, lead-acid and nickel-based batteries. Gaston Planté invented the rechargeable lead-acid battery in 1859 and applied it in early EVs [12]. Currently, EVs using lead-acid batteries as power batteries are rare, and only some two-wheelers and electric forklifts are still using them. The advantages of lead-acid batteries include low

price, high stability, and high availability. However, lead-acid batteries have shortcomings that restrict their development. Firstly, lead is seriously harmful to human health; therefore, it is necessary to establish a complete battery recycling system to avoid lead-acid batteries polluting the environment. Secondly, compared with lithium-ion batteries, lead-acid batteries have lower specific energy and energy density. The trend of EV batteries is to store more energy in a limited volume. Therefore lead-acid batteries are seldom used as power batteries for electric vehicles. However, lead-acid batteries are not useless in electric vehicle systems. Lead-acid batteries are now most commonly used in start–stop systems in automobiles. Specifically, they can supply power to the low-voltage batteries of an electric vehicle, as well as wake up the high-voltage power battery.




(**a**)




(**b**)

**Figure 2.** Global battery industry. (**a**) Global battery demand. (**b**) Demand for batteries by region. Source: information from [11] and drawn by the authors.

The most popular batteries in today's EVs are lithium-based batteries, also considered the most suitable choice for developing the new generation of EVs [13]. Table 1 shows the performance of the lithium-based batteries and other batteries. Lithium-based batteries can be divided into lithium-ion batteries and lithium-metal batteries. In Table 1, specific energy refers to the amount of energy stored per unit mass of the battery, typically expressed in watt-hours per kilogram (Wh/kg). It reflects the energy density of the battery, with a higher value indicating that the battery can provide more electrical energy for the same weight. Specific power, on the other hand, refers to the power output per unit mass of the battery, measured in watts per kilogram (W/kg). It reflects the battery's discharge capability, with a

higher value indicating that the battery can deliver greater power in a short period of time. Cycle life refers to the number of charge–discharge cycles a battery can undergo while maintaining its performance, usually expressed as the number of cycles. A longer cycle life means a longer usable lifespan for the battery. These parameters collectively determine the performance and application range of lithium-ion batteries. Among them, lithium-ion battery development is more mature. Lithium-ion batteries are superior in terms of high energy efficiency and power density. They simultaneously have an immense power storage capacity with a small size and are lightweight [14]. Moreover, other advantages of lithium-ion batteries include a broad temperature range of operation, rapid charge capability, no memory effects, relatively long cycle life, and low self-discharge rate [15,16].

**Table 1.** Comparison of the most used batteries. Source: data from [11].

| Types | | Specific Energy (Wh/kg) | Specific Power (W/kg) | Cycle Life | Advantages | Disadvantages |
|---|---|---|---|---|---|---|
| Lead-acid | | 30–50 | 150–200 | 400–800 | Low cost, mature technology, high output current, nonflammable, resistant to vibration, and durable | Large weight and volume, lower specific energy, lower energy density, and heavy pollution |
| Nickel-based | Ni-Fe<br>Ni-Cd<br>Ni-Zn<br>Ni-MH<br>Ni-H2 | 35–80 | 150–450 | 800–2000 | Mature technology, high stability, low cost, and high specific power | Existence of a memory effect, low energy efficiency, and low specific energy |
| Zinc-based | Zn-Mn<br>Zn-Ni<br>Zn-C<br>Zn-Br | 30–200 | 50–500 | 10–2000 | Low cost (abundant zinc material), high safety (not easy to burn or explode), and environmentally friendly (some types are easy to recycle) | Lower energy density (compared to lithium-ion batteries), limited cycle life (some types are not rechargeable or have fewer cycles), and technical limitations (some types are still under development) |
| Lithium-based | LCO<br>LMO<br>LFP<br>NMC<br>NCA<br>LTO | 120–300 | 200–450 | 600–3000+ | High energy efficiency, high specific power, long cycle life, and light weight | Depending on the rare metal, the price of lithium fluctuates, and security needs to be improved |
| | Lithium-metal | N/A | N/A | N/A | | |

Lithium-ion batteries have become crucial in EVs [17,18]. Since 2006, the volume of research publications on lithium-ion battery technology and application has increased [19]. Previous studies have reviewed lithium-ion battery technology for EVs from different perspectives. In 2010, Jürgen Garche and Bruno Scrosati [20] elaborated on the principle of lithium batteries and pointed out some existing problems. Some scholars also discussed the battery management system of lithium-ion batteries in the literature [19,21]. Raw materials of lithium-ion batteries, which have a higher energy content, were discussed in [22]. Meanwhile, the commercial application of lithium-ion batteries in EVs has been the focus of attention, which was discussed in detail in the literature [7,23].

This paper aims to allow readers to quickly and clearly understand the advantages and disadvantages of various commercial lithium-ion batteries and the future development direction. Major contributions are as follows:

(1) This paper mainly classifies according to materials, summarizes the characteristics of different types of lithium-ion batteries, and elaborates on their commercial applications and prospects in EVs. Compared with similar papers, this paper presents new views on the commercialization prospects of lithium-ion batteries with different materials.
(2) Previous papers have rarely introduced specific lithium-ion battery products for commercial electric vehicles. This article details representative commercial products, including the blade battery and the 4680 cells, to help readers intuitively understand the characteristics of lithium-ion battery products in detail.
(3) Some cutting-edge technologies of lithium-ion batteries, including liquid–solid electrolyte technology, in situ polymerization technology, and the pouch battery, are discussed, which may have a significant impact on the development of lithium-ion batteries in the future.
(4) Finally, the challenges facing lithium-ion batteries at present are summarized comprehensively, and the future development direction of lithium-ion batteries is discussed, including some specific indicators and measures that future lithium-ion batteries should achieve.

## 2. Lithium-Ion Batteries

Lithium has the highest electrochemical potential, making it one of the most reactive metals. Lithium-based systems open a new era for high-energy and high-power batteries, and more and more often replace other battery technologies, such as lead-acid and nickel-based systems [5]. Lithium-ion batteries are already in heavy use. However, most lithium-metal batteries are still in the experimental stage.

### *2.1. Operational Principle of Lithium-Ion Batteries*

A lithium-ion battery is a kind of energy storage system that relies on a double-electrode insertion reaction, and the lithium ion acts as a charge carrier. The main components of a lithium-ion battery include a positive electrode, a negative electrode, an electrolyte, and a diaphragm. The cathode of a lithium-ion battery is mainly composed of lithium-ion compounds that provide lithium ions to the battery. The anode material is mainly graphite, and its main role in the battery is to store lithium ions. The liquid electrolyte includes a mixture of lithium salt and organic solvents. At present, the most commonly used electrolyte is LiPF6, and the commonly used organic solvents are carbonated organic solvents, carboxylate organic solvents, ether organic solvents, etc. The electrodes are separated by an insulating layer called a diaphragm, which is a special composite film. Commonly used materials include single-layer PP film, PE film, and PP/PE/PP three-layer composite film. The function of the diaphragm is to prevent electrons from shuttling freely between the positive and negative electrodes, but it cannot prevent the passage of lithium ions in the electrolyte. Electrons cannot exist alone from the carrier, and the diaphragm is an insulator and cannot be used as a carrier for electrons, so it does not conduct electricity. At the same time, the role of the diaphragm also includes preventing short circuits in the anode and cathode when the liquid electrolyte dries out due to internal faults or abnormal conditions.

The working principle of lithium-ion batteries is shown by Equations (1)–(3) and Figure 3. When the charger connects to both ends of the battery, active lithium atoms ($Li^+$) are separated from lithium-ion metal oxide at the positive pole and produce an electron ($e^-$) simultaneously. The positively charged lithium ions pass through the separator under the action of the electric field force, and flow through the electrolyte and get trapped in the graphite layers. Negatively charged electrons cannot pass through the separator

and electrolytes. Therefore, they are forced to flow through the charger to the negative electrodes. The charging process is over when all lithium ions in the battery reach the negative poles. The battery is thus fully charged.

During the discharge process, the cell connects across a load. At this moment, lithium ions move back to the positive electrode through the electrolyte, and electrons return to the positive pole through the external circuit. Lithium ions and electrons that move to the positive pole get deposited on the cathode as stable metal oxide. The discharge process is over when all the lithium ions return from the anode to the cathode. The battery needs to be recharged.

Taking $LiCoO_2$ as an example, the chemical reaction equations that occur in a typical lithium-ion battery are as follows [24]:

At the cathode:

$$6C + xLi^+ + xe^- \Leftrightarrow Li_xC_6 \quad (1)$$

At the anode:

$$LiCoO_6 \Leftrightarrow xLi^+ + Li_{1-x}CoO_2 + xe^- \quad (2)$$

Overall:

$$Li_xC_6 + Li_{1-x}CoO_2 \rightleftarrows 6C + LiCoO_2 \quad (3)$$

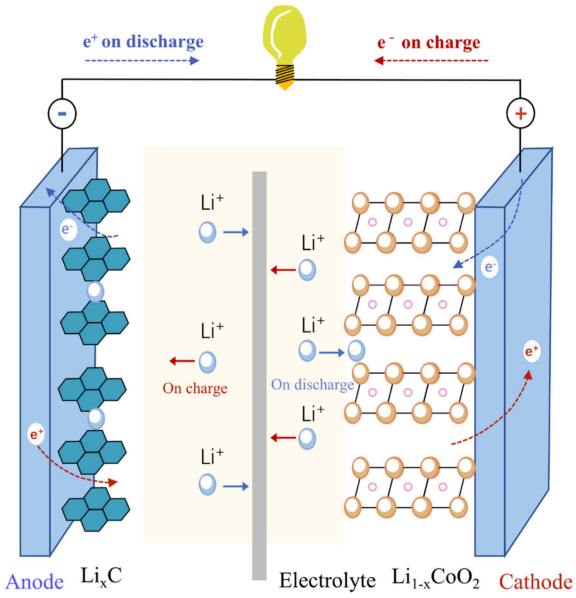



**Figure 3.** Lithium-ion battery working principle. Source: from [25] and redrawn by the authors.

### *2.2. Electrolytes for Lithium-Ion Batteries*

#### 2.2.1. Development of Traditional Electrolyte Technology

From the perspective of roles played, the electrolyte is the key material that affects the performance of lithium batteries in terms of high voltage and high specific energy. With the continuous development of EVs, the continuous development and iteration of new technologies and processes for lithium-ion batteries, such as higher nickel, high voltage, high specific energy, high safety, and other aspects of the electrolyte, create higher demands. High-nickel cathode material is currently the mainstream technology route for high-energy-density lithium batteries. From the perspective of resource utilization, high-nickel cathode materials can save the use of the rare and expensive element cobalt because of its high nickel and low cobalt characteristics, and at the same time, it has the advantages of high capacity and high-rate performance. But the increasing proportion of nickel and the use of a silicon-carbon anode brings new challenges to electrolyte R&D and production. In

addition, the higher the voltage, the greater the ability of the electrolyte to decompose or degrade the performance and safety of lithium-ion batteries.

Current research on electrolytes mainly uses lithium hexafluorophosphate as the lithium salt and single or mixed carbonate solvents as the primary solvent, which mainly includes ethylene carbonate (EC), dimethyl carbonate (DMC), ethyl methyl carbonate (EMC), diethyl carbonate (DEC), and propylene carbonate (PC) [26]. Traditional electrolytes usually decompose when the working voltage is too high (over 4.3 V). High-voltage materials can be used to improve electrolytes' ability to withstand voltage, including high-pressure solvents, high-pressure additives, high-concentration lithium salt electrolytes, etc. Fast charging is also essential for electrolyte development for high-power lithium-ion batteries used in EVs. Fast charging means high power. Lithium battery high-power electrolytes mainly focus on two aspects of the problem: first, in high-rate charging under the solid electrolyte interphase (SEI) membrane, charge migration impedance increases so that the charging process of electrode polarization increases and, second, lithium batteries easily produce the lithium dendrite phenomenon in the late stage of constant-current charging, resulting in poor battery performance [27]. To solve these problems, the high performance of the battery can be improved by adding lithium salts that facilitate high-rate charging and discharging, and the charge transfer impedance of the electrode interface under high-rate charging and discharging can also be reduced by adding high-performance additives, or by adding lithium salt deposition improvers to prevent the growth of lithium dendrites during high-rate charging [26].

However, the disadvantages of liquid electrolytes are electrochemical instability, potential hazards, and low ion selectivity. Solid electrolytes offer excellent safety and thermal stability compared to liquid electrolytes, as they can provide a barrier to separate the positive and negative electrodes and prevent thermal runaway. In addition, the solid electrolyte can effectively inhibit the formation of lithium dendrites.

Among them, inorganic solid electrolytes, solid polymer electrolytes, and composite electrolytes have been extensively studied in lithium-ion batteries.

Despite the significant advantages, solid electrolytes still have many drawbacks that need to be improved, such as the ionic conductivity of solid electrolytes is usually lower than that of liquid electrolytes. The preparation and manufacturing process of solid electrolytes is relatively complex, and today's solid electrolyte manufacturing methods still face some challenges, such as material purity, process stability, and capacity [28]. Meanwhile, the interfacial stability between solid electrolyte and electrode materials is a complex problem [27].

#### 2.2.2. High-Energy-Density In Situ Polymer Technology

Solid electrolytes can be divided into inorganic solid electrolytes (ISEs) and polymer electrolytes (PEs). ISEs have high mechanical strength, high ionic conductivity, and a high ion mobility number, but they make it challenging to form close contact with the electrode, thus limiting the practical application range [29]. Compared to ISEs, PEs are more flexible and allow for better interface compatibility with electrodes.

PEs can be classified into three types, namely, gel polymer electrolytes (GPEs), solid polymer electrolytes (SPEs), and composite polymer electrolytes (CPEs) [30].

The traditional manufacturing process of PEs is an ex situ process, where PEs are stored as independent films outside the battery and assembled inside the battery. In practice, due to the existence of voids inside the electrodes, the physical contact between the ex situ polyethylene and the electrodes could be better, and the use of the non-in-situ process dramatically reduces the utilization of the active material. In order to enhance the interfacial contact and expand the utilization of active materials, in situ polymerization

of polyethylene was proposed. In situ polymerization allows the conversion of liquid electrolytes to polyethylene directly inside the battery [31].

In situ GPEs reduce the risk of solvent leakage compared to common liquid electrolytes. They have a tighter electrode/electrolyte interface compared to non-in-situ GPEs. The flexible polymer network formed by in situ polymerization can improve the battery's mechanical strength and inhibit the growth of lithium dendrites [32].

SPEs can enhance safety. Lithium-based batteries with in situ SPEs have lower interfacial impedance than non-in-situ SPEs due to the ability of monomers to penetrate voids and polymerize in situ to fill them. However, the low ionic conductivity of polymers limits the application of SPEs.

CPEs can improve batteries' mechanical and electrochemical properties, such as ionic conductivity, lithium-ion mobility number, cycling stability, and lithium dendrite inhibition. Compared to non-in-situ CPEs, in situ CPEs can reduce filler settling and agglomeration, improve inorganic/polymer interfacial compatibility, and tightly fill the electrolyte interface. Solid-state lithium batteries with in situ CPEs have less polarization and a longer cycle life. Applied to EV power batteries, they can increase the life of EVs.

In the future, the principles of in situ polymerization methods need to be further investigated, and the chemical/electrochemical reaction mechanism of in situ polymerization cells remains challenging. Optimization of the in situ polymerization process is needed to further improve the energy density, price, durability, and safety of lithium-ion batteries and other types of lithium batteries [33].

### *2.3. Anode and Cathode Materials for Lithium-Ion Batteries*

The anode and cathode of lithium-ion batteries are generally intercalation compounds from which Li+ can diffuse out or back in. The cathode material of the commercially available lithium-ion batteries is lithium metal phosphate [34]. Common examples of the materials include lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA) [16].

Negative electrodes or the anodes of the lithium-ion batteries are generally carbon-based electrodes and lithium titanate (LTO). Furthermore, a new type of electrode development includes lithium-metal and lithium-metal alloys, with a particular focus on lithium-silicon alloys and conversion electrodes.

#### 2.3.1. Lithium Cobalt Oxide

Sony created lithium cobalt oxide in 1991, and Mizushima improved the material [35,36]. It was the first successfully commercialized lithium-ion battery. The battery consists of a cobalt oxide cathode and a graphite carbon anode. LCO has a layered structure with oxygen in a cubic close-packed arrangement, and the lithium could be removed electrochemically, thus making it a viable cathode material [37,38]. The specific energy of LCO is high, which makes it a popular choice for mobile phones, laptops, and digital cameras. However, Li-cobalt has a short life and limited load capacities and cannot be charged and discharged at currents out of its range [39,40]. Furthermore, its thermal ability is poor and can easily become a potential fire hazard. The microstructure of the LCO material is like a sandwich cake, with cobalt-oxygen forming a compact layer with covalent properties (also called the main crystalline layer), while lithium is between the two cobalt-oxygen layers, utilizing the oxygen on the periphery of the cobalt-oxygen layer in the form of lithium-oxygen octahedra (also called the inter-crystalline layer), and has a good ion mobility. But in this structure, on the one hand, the lithium ions partially migrate out in the charging and discharging process (de-embedding) and, on the other hand, it also bears the upper and lower two cobalt-oxygen layers of structural support.

This also means that positively charged lithium ions, in the form of electrostatic gravitational force, and the two originally negatively charged, mutually exclusive cobalt-oxygen layers, "stick" together. Obviously, when lithium ions from the LCO are de-embedded out more and more, the lithium ions that can "stick" to the cobalt-oxygen layer will be less and less, and could even lead to the final cobalt-oxygen layer between the lithium ions falling apart. This is the main culprit of LCO battery's safety hazard, "the original sin".

#### 2.3.2. Lithium Manganese Oxide

LMO was introduced in the early 1980s [41]. The 3D spinel architecture of the LMO was organized as a diamond shape, allowing the particles to steam on the electrode to enhance current dealing, reduce internal resistance to charge quickly, and discharge with a high current. Li-manganese can discharge at currents of 20–30 A in a 18,650 package [21]. LMO provides better thermal stability [42]. However, the capacity of lithium manganese is approximately 33% lower than Li-cobalt, which is 100 to 120 mAh/g Moreover, because of considerable manganese dissolution in the electrolyte at elevated temperatures, it has a higher capacity loss on storage or cycling [43].

The poor high-temperature performance of LMO is mainly caused by the following reasons: (1) The Jahn–Teller effect and the formation of a passivation layer. There is a capacity loss due to the incompatibility of the distorted square crystal system on the surface with the cubic crystal system inside the particles, which destroys the integrity of the structure and the effective contact between the particles, thus affecting the Li+ diffusion and the inter-particle conductivity [44]. (2) Dissolution of Mn: trace water present in the electrolyte reacts with LiPF6 in the electrolyte to form HF, leading to a disproportionation reaction of $LiMn_2O_4$, dissolution of $Mn^{2+}$ into the electrolyte, and disruption of the spinel structure, resulting in the capacity degradation of the LMO cell. (3) The electrolyte decomposes at high potential, forming a $Li_2CO_3$ film on the LMO surface, which increases the polarization of the cell, thus causing the spinel $LiMn_2O_4$ capacity to decay during cycling. Oxygen defects are a major cause of LMO high-temperature cycling decay because LMO high-temperature cycling decay is always accompanied by a decrease in the valence of Mn.

#### 2.3.3. Lithium Iron Phosphate

In 1996, researchers at the University of Texas in Austin found that phosphate materials could be used in lithium-ion batteries as positive electrodes [45,46]. LFP offers incredible electrochemical performance with low resistance, which makes it possible with nano-scale phosphate cathode material. Phosphates are steady in overcharged conditions and can tolerate high temperatures without breaking down [19]. Phosphates are not prone to thermal runaway and will not burn. Therefore, these batteries have a wide temperature range and can operate between +60 °C to −30 °C and between −50 °C and +60 °C, respectively [47]. These features have attracted significant attention. LFP is an olivine crystal structure that has a smaller crystal lattice deformation in the sufficient electric discharge process. Its structure is stable and safe, and its cycle life is long. LFP can bear oxidation and an acidic environment, and its electrolyte has more choices [48]. At the same time, through the research of Minakshi et al., LFP was found to be easy to be used as a material for water-based batteries [49,50].

#### 2.3.4. Lithium Nickel Manganese Cobalt Oxide

NMC is an extremely popular battery type used by electric vehicle manufacturers. Chemistry calculates the theoretical capacity of NMC to be about 275 mAh/g, but its actual capacity depends on the ionic ratio of the metal elements in the material. Because Ni can cycle between $Ni^{2+/3+}$ and $Ni^{3+/4+}$ redox couples without large variations in voltage

during the charge/discharge process, layer-structured Ni-rich NMC ($LiNi_xMn_yC_{o1-x-y}O_2$, $x \geq 0.5$) cathodes (e.g., $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC532), $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622), and the most recent $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811)) have been developed. Here, the main advantage of Ni-rich materials is their high discharge capacity (200–220 mAh/g), which represents a large increase in energy density (~800 Wh/kg), as compared with conventional $LiCoO_2$ (~570 Wh/kg) and $LiMn_2O_4$ spinel (~440 Wh/kg) materials [51]. The high Ni cathode (NMC811) exhibits a higher capacity and operating voltage because Ni is the main redox substance, Mn serves to maintain the cycle life and safety of the battery, and Co is responsible for increasing the electrical conductivity of the electrons. However, the thermal stability of the NMC battery is poor [52]. At present, the NMC battery with 60% nickel content has been commercialized, but the nickel-rich NMC cathode with more than 80% nickel content has difficulties in the electrode production process. During the synthesis of NMC (Ni $\geq$ 80%), unstable properties originated from the precursors that resulted as the residual compounds of the lithium in the final product. Nickel-rich NMC is the most serious candidate for the batteries that are used in EVs. Depending upon the mixing proportion of the Ni content in NMC, there are certain advantages and disadvantages. Even though the theoretical capacities of all the compositions of NMCs (NMC 111 to NMC 811—these numbers represent the atomic ratios of Ni, Mn, and Co, respectively) are similar, the reversible specific charge capacities increase from the lower Ni composition NMCs to the higher Ni composition NMCs (i.e., from 163 mAh/g for NMC-111 to more than 200 mAh/g for NMC-811) [53].

#### 2.3.5. Lithium Nickel Cobalt Aluminum Oxide

NCA has been around since 1999 for special applications. It has a small amount of the world market share [54]. It shares similarities with NMC by offering high specific energy, specific power, and a long lifespan [19]. The theoretical specific charge capacity of NCA can reach 256 mAh. $LiNi_{1-x}Co_xO_2$ phases had good cycling properties with high lithium diffusion in the interslab spaces. NCA is less safe than the others listed above and, as such, requires special safety monitoring measures to be employed for use in EVs. NCA also has higher manufacturing costs, limiting its viability for use in other applications [21]. Currently, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ with Al content of 5% is the most important cathode material for commercial use, with high specific energy (about 200 mAh/g) and better specific power, as well as lifetime [55]. However, the main problems affecting the large-scale application of NCA include Al distribution in NCA particles, capacity degradation during long-term cycling, and so on. To solve these problems, doping manganese and titanium in NCA can improve the chemical properties of the cathode. Due to the introduction of $Mn^{4+}$ ions and $Ti^{4+}$ ions into the octahedral lattice space of lithium ions, the layer spacing of the material is expanded, thus increasing the structural volume [53].

#### 2.3.6. Carbon-Based Electrodes

Carbon, made of synthetic graphite, is a traditional material for battery anodes. Since the discovery that graphite can efficiently embed and expel lithium ions and that the process is reversible, it has been widely used in lithium batteries. Graphite is a highly conductive material with low cost, which can maintain stable electrochemical performance and low-volume expansion [56]. This feature is helpful during frequent lithium intercalation/deintercalation processes. In addition, carbon-based electrodes have low redox potential, high Coulomb efficiency, and a long cycle life. The disadvantage of graphite is that when the battery is rapidly charged or discharged under extreme conditions, the organic electrolyte and graphite will have an irreversible parasitic reaction. In a thermal runaway, carbon will react with oxygen, and the electrode will catch fire [57].

#### 2.3.7. Lithium Titanate

LTO has been widely used in batteries since the 1980s [34]. LTO has a spinel architecture and can replace the graphite electrode of a lithium battery, and the counter-electrode can be lithium manganese oxide or NMC [41]. Compared with graphite electrodes, LTO has the following advantages: high reversibility and stability, and the zero-strain effect makes the change in cell volume during lithium-ion insertion and de-embedding negligible. It also has a higher working potential plateau to avoid SEI formation and lithium dendrite deposition. LTO is typically 1.55 V and shows a high capacity (can reach 100 Ah), charge and discharge rate (support 10 C), and lifespan compared to a typical lithium-ion battery [58]. Moreover, the LTO battery has good performance at low temperatures. Because its specific energy is not high, the developments and research focus on enhancing it and reducing the price [59].

#### 2.3.8. Silicon (Si) Carbon Composite Material

For Si, as a crystalline material, its capacity to accommodate lithium ions far exceeds graphite, reaching 4200 mAh/g. Moreover, silicon is widely distributed, and the cost is low. However, Si, as the negative electrode of lithium-ion batteries, will have a volume expansion problem, reaching 280%. In order to solve these problems, a Si load material is used, that is, a Si and C composite. This load material can alleviate the volume expansion problem and solve the problem that Si is not very conductive. The first silicon-based material to be industrialized was a composite of $SiO_2$ and C. It has been used in some car models [60,61].

Figure 4 compares the performance of different electrode materials, including specific energy, specific power, safety, cost, cycle life, and performance. The performance represents the battery's condition in extreme temperatures, such as driving an EV in hot summer or under zero temperature. The farther the colored shape extends along a given axis, the better the performance in that attribute. The following criteria were used to plot Figure 4. First, each layer of hexagons represents a grade. The largest hexagon represents the first notch, i.e., the best performance, and the smallest hexagon represents the fifth notch, i.e., the worst performance. Taking the anode material as an example, LFP had the best cycle life, specific power, and safety, so it was set as the first grade. Other types of batteries were evaluated in different grades by comparing with LFP. The specific energy took NCA as a reference, because its specific energy was relatively the largest.

The properties of the different anode and cathode materials discussed above are summarized in Table 2.

**Table 2.** Comparisons of different lithium-ion battery materials: (a) cathode materials and (b) anode materials.

| Materials | Specific Energy | Specific Power | Safety | Cost | Lifespan | Performance |
|---|---|---|---|---|---|---|
| (a) | | | | | | |
| LCO | 3 | 2 | 1 | 2 | 2 | 3 |
| LMO | 2 | 4 | 4 | 4 | 2 | 2 |
| NMC | 4 | 4 | 2 | 2 | 3 | 4 |
| NCA | 5 | 5 | 1 | 2 | 3 | 4 |
| LFP | 2 | 5 | 5 | 4 | 5 | 2 |

**Table 2.** *Cont.*

| Materials | Specific Energy | Specific Power | Safety | Cost | Lifespan | Performance |
|---|---|---|---|---|---|---|
| | | | (b) | | | |
| C | 5 | 2 | 3 | 5 | 3 | 5 |
| LTO | 2 | 5 | 5 | 1 | 5 | 4 |
| Si/C | 4 | 2 | 2 | 5 | 4 | 4 |

LTO: lithium titanate; LMO: lithium manganese oxide; NMC: lithium nickel manganese cobalt oxide; NCA: lithium nickel cobalt aluminum oxide; LFP: lithium iron phosphate; C: graphite (carbon); LTO: lithium titanate oxide; Si: silicon; LCO: Lithium Cobalt Oxide.

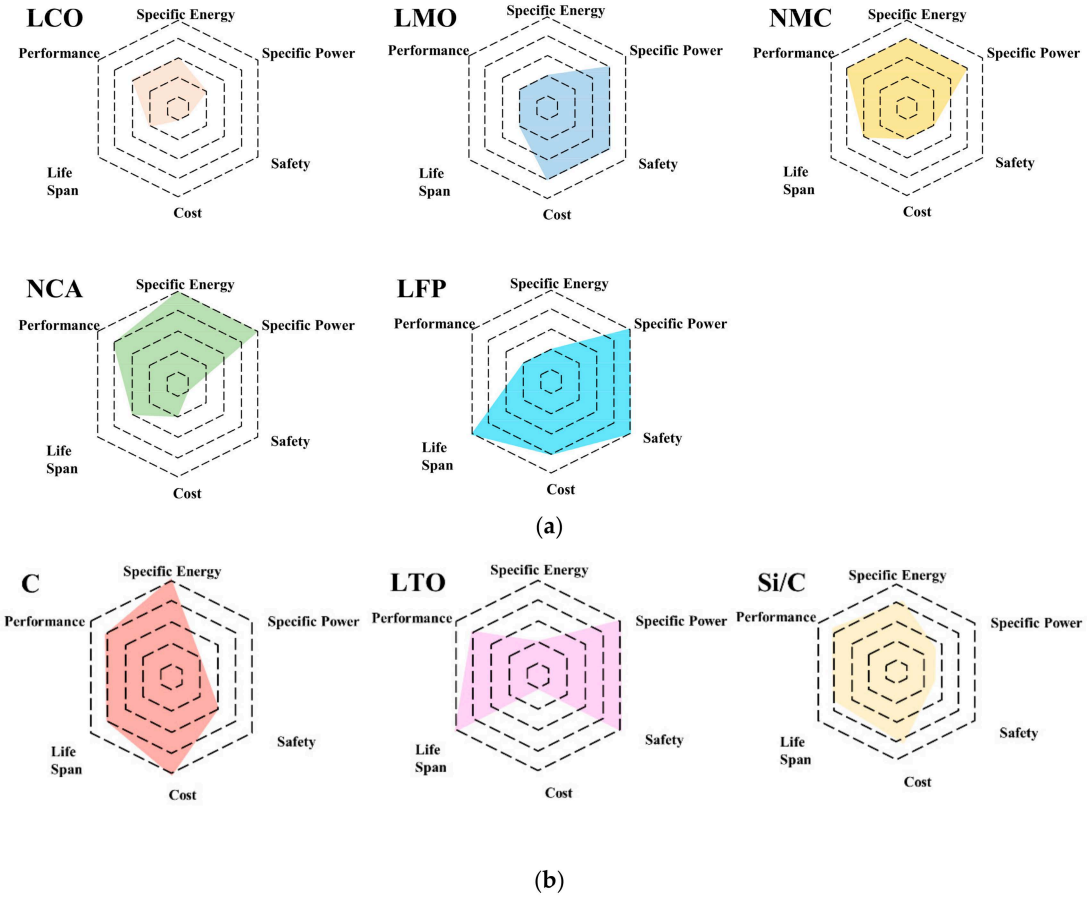



**Figure 4.** Summary of the features of the most common cathodes and anodes of lithium-ion batteries: (**a**) cathodes and (**b**) anodes. Data were from [11,21,62].

## 3. Commercial Application of Lithium-Ion Batteries in EVs

A few years ago, some car manufacturers focused on other battery technologies, such as Ni-Mn in the case of Mitsubishi, but now, lithium-ion batteries are the mainstream of the EV industry [63]. The main advantage of lithium batteries is their high specific energy, making them smaller and lighter. Moreover, they have a long cycle life. This section will focus on the significant lithium-ion battery applications in EVs. The advantages and disadvantages of lithium-ion batteries with cathode materials mentioned above in the commercial application of EVs will be discussed in detail.

### *3.1. Traditional Cathode Materials LCO and LMO*

As described in the previous section, LCO was the first successfully commercialized lithium-ion battery. Portable electronic devices have widely used LCO. The excellent cycling performance and high discharge voltage made LCO one of the commercial lithium-ion

batteries for the previous-generation EVs [7]. However, LCO has many fatal shortcomings, which limits its further development in EVs. First, the thermal stability of LCO is inferior, which means that when lithium metal oxide is heated above a certain point, it will release heat and oxygen, causing the battery to lose control and burst into flames. LCO has the lowest thermal stability [24]. Second, LCO has quick capacity decay during the deep cycle [64]. Third, LCO cathodes are expensive because of the high cost of cobalt. The Democratic Republic of the Congo contributes more than half of the sourced cobalt. According to the data from the London Stock Exchange, the cobalt price increased significantly from August to November 2021. In summary, up to now, there is not much room for developing LCO as a cathode material in EVs. Ternary lithium batteries usually use cobalt in EV applications, which will be introduced in detail below.

In August 2019, the installed capacity of the Chinese enterprise Weihong power battery was 91.83 MWh. They extensively use a soft-pack lithium manganate battery. LMO is also widely used in two-wheeled vehicles [65]. The Chinese enterprise Xingheng Power focuses on the LMO route in the light EV market. The LMO currently used by Xingheng power supply is not lithium manganate in the conventional sense. However, the proportion of lithium manganese is adjusted, and the power lithium manganate doped with metal elements has significantly improved its cycle performance. The lithium battery warranty of Xingheng power light vehicles can fully meet the five-year warranty or even longer. In traditional EVs, most lithium manganese batteries also mix with ternary materials, improving the specific energy and prolonging the lifespan. Multiple EV manufacturers have used LMO-NMC, including Nissan Leaf, Chevy Volt, and BMW-i3 [66].

Furthermore, other models have used LMO-NCA. As a lithium battery technology route with the earliest industrialization and the most mature technology application in the world, LMO series batteries have a certain development potential in the future, not only in the field of two-wheel EVs, which are widely used now, but also in four-wheel EVs.

### *3.2. Ternary Lithium and LFP*

Ternary lithium batteries and LFP batteries are the two most mainstream batteries in the current lithium-ion battery market. In the field of power batteries in China, the output of LFP batteries accounted for 57.1%, and the output of ternary lithium batteries accounted for 42.7% in 2021. These two types of batteries have advantages and disadvantages in different aspects.

First, in terms of energy density, ternary lithium batteries are significantly better than LFP batteries. The energy density of a single LFP battery is about 180 Wh/kg, while the energy density of a single ternary lithium battery can exceed 250 Wh/kg. Secondly, regarding the crucial low-temperature performance of the battery, the ternary lithium battery is better than that of the LFP battery. Due to the low conductivity of LFP material, the capacity retention rate of LFP batteries at $-20$ °C is only about 60%, compared with the expected temperature. Moreover, the ternary lithium battery of the same system can reach more than 70% [67].

However, LFP batteries also have many advantages that ternary lithium batteries do not have. The cost of an LFP battery is 20% lower than that of a ternary lithium battery. In terms of cycle life, the cycle life of an LFP battery is much higher than that of a ternary lithium battery. According to the research, the maximum cycle life of an LFP battery can reach 9000 times, while the maximum cycle life of ternary lithium can only reach 2500 times [68]. The safety of a ternary lithium battery is worse than that of an LFP battery. A recent report from China's National Big Data Alliance of New Energy Vehicles showed that 86% of EV safety incidents reported in China from May to July 2019 involved EVs powered by ternary batteries, and only 7% were from those with LFP batteries.

3.2.1. High-Performance Lithium Ternary

A ternary lithium battery refers to a lithium battery using nickel, cobalt, and manganese transition metal oxides as cathode materials. Ternary materials combine the advantages of LCO, LMO, and lithium nickel oxide (LNO) to a certain extent, making their performance superior. This section mainly introduces the application of NMC and NCA ternary materials in EVs.

NCA material is primarily composed of nickel (Ni), cobalt (Co), and aluminum (Al), with the nickel content typically exceeding 80% and the cobalt content being relatively low. The addition of aluminum enhances the thermal stability and safety of the material. NCA offers high energy density and excellent range performance, but it comes with higher costs and stringent manufacturing requirements. It is mainly used in applications demanding extremely high energy density, such as Tesla's electric vehicles. On the other hand, NMC material consists of nickel (Ni), cobalt (Co), and manganese (Mn), with adjustable ratios (e.g., NCM 811 and NCM 622). Nickel provides high energy density, cobalt improves conductivity and stability, and manganese enhances structural stability and safety. NMC strikes a better balance among energy density, cycle life, and cost, and the inclusion of manganese gives it superior thermal stability compared to NCA. As a result, NMC is widely used in electric vehicles, energy storage systems, and other fields. In summary, NCA is more suitable for scenarios pursuing ultimate energy density, while NMC offers greater advantages in overall performance and cost-effectiveness.

NMC is one of the most successful lithium-ion systems combining high nickel capacity and low manganese internal resistance [69]. Like NMC, NCA, a relatively new cathode, has a very high specific energy, energy density, and good lifespan. The application of NCA has been around since 1999 as an upgrade to LNO.

Panasonic launched the cylindrical 18,650-type lithium-ion battery in 2006, using NCA as the cathode material and commercializing Tesla's cells [70]. Many other models also use NCA/C technology, for example, the Mercedes-Benz S400 (2010), and the Tesla S (2012), X (2015), and 3 (2017). Panasonic/Sanyo commercialized the NMC/C prismatic cell for VW e-Golf (2015), and Toshiba commercialized the NMC/LTO prismatic cell for Honda Fit EV (2013) [70,71].

Tesla has been using ternary lithium technology for many years. They favor cylindrical batteries. From the 18,650 cylindrical batteries to the 21,700 cylindrical batteries to the latest 4680 model, Tesla has always chosen high-nickel cathode materials, including NCA and NMC. Among them, the newly released 4680 cells with tabless technology have attracted wide attention [72]. Numeral 4680 indicates that the cylindrical battery has a diameter of 46 mm and a height of 80 mm. As shown in Figure 5, the battery tab is a metallic conductor that extends from the core of the battery to imprint the positive and negative electrodes. It is typically made of metal materials, such as aluminum (used for the positive electrode) and copper (used for the negative electrode). The function of the tab includes conducting electricity and establishing connections. The tab facilitates effective transmission of chemical energy within the battery to external electrical energy, ensuring smooth flow in and out of the battery, while also serving as a bridge for energy exchange between the battery and its surroundings. More tabs mean the cell has less resistance than one tab. The volume is significantly increased compared to the battery models used by Tesla. The most direct advantages of the larger size are that it can save material costs, reduce the number of cells in the battery pack, and reduce the pressure of the BMS battery management system. However, the large-volume battery also has the disadvantage that the current of the large-volume battery flows in the battery for a longer distance, which will cause the battery to overheat and reduce the charging efficiency. The 4680's exquisite tabless design overcomes these shortcomings. The contact point of the

positive and negative poles is when the cell is charged and discharged. The current must flow through the tab to connect outside the battery. If there is only one tab, all electrons need to cross the entire length of the cell to reach the tab, which makes the cell's resistance increase and the cell's temperature unbalanced. In addition to welding the electrode tab to connect the electrodes and the cells, the uncoated bottom edge of the electrode works as the tab to connect with the specially designed multi-contact area case bottom. These high-contact areas can significantly reduce the impedance and the heat generated in the charge and discharge process [73,74]. The popular understanding is that point-to-point transmission has changed to face-to-face transmission, the conduction area has become more significant, and the transmission efficiency has increased. The tag has resistance, and removing the tag is equivalent to solving part of the heat source. This design effectively avoids the generation of overpotential at the tag and naturally reduces the accumulation of heat. It is precisely because the heating capacity of the 4680 cells is within the controllable range that Tesla can expand the battery and increase the charging current to improve the charging efficiency.

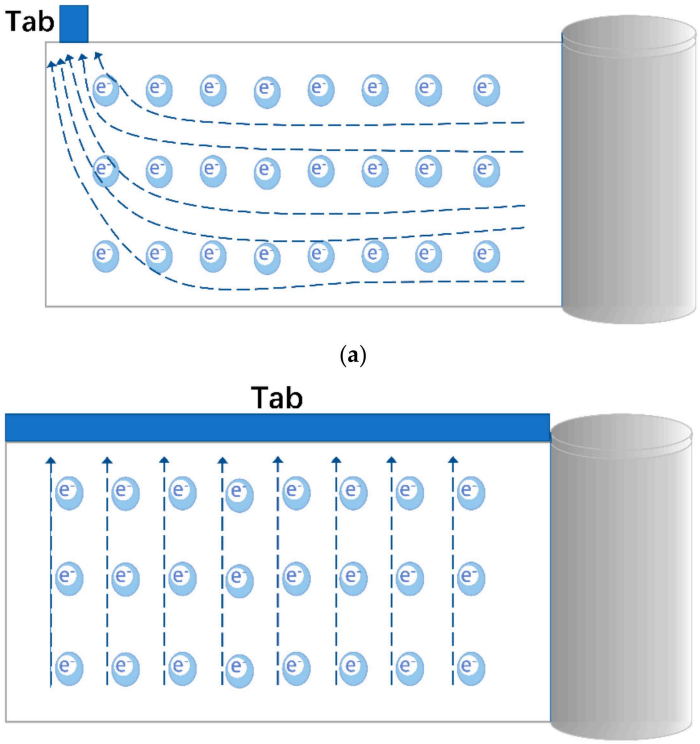



**Figure 5.** Flow diagram of electrons in different types of batteries. (**a**) Normal cell: having only one tab, it takes a long time for electrons to flow to the tab, causing the temperature to become more severe. (**b**) The 4680 cells with tab-less technology shorten the distance of electrons to the tab, reducing the temperature.

Compared with 18,650 and 21,700 batteries, the advantages of 4680 batteries are summarized as follows: (1) Higher energy density. The 4680 batteries are larger and more capable of holding more active materials, thus storing more power in the same space and increasing the range of electric vehicles. (2) Better heat dissipation. The larger size helps to dissipate heat better, lowering the temperature of the battery during operation and improving the safety and service life of the battery. (3) More flexible battery pack design. The 4680 batteries can reduce the number of batteries in an electric vehicle, simplify the structure of the battery pack, and reduce the complexity of assembly and management.

3.2.2. Fast-Growing LFP

LFP is famous for its stable cell chemistry and strong safety profile [75]. In terms of price, the price of LFP is low because the primary material is iron. The advantages of applying LFP in EVs are the high pulse-rate capability of up to 10 C and 20 C pulse discharge, excellent thermal stability, long cycle life, enhanced safety, tolerance when abused, and advanced environmental friendliness after being retired [76]. EVs using LFP batteries can provide full power before full discharge and charge quickly within 2.5 h. The disadvantage of LFP is its lower operating nominal voltage of 3.2 V, which reduces the energy density. Low energy density reduces the ability of EVs to use LFP batteries for long-distance travel [77].

At present, LFP has a wide range of applications in EVs. Since 2020, the LFP market in EVs has entered a new growth cycle. People advocate to develop cobalt-free batteries so that LFP returns to the center of the stage. In China, relevant data show that the installed capacity of LFP in 2021 exceeded that of ternary lithium batteries. The growth rate was much higher than that of ternary lithium batteries. In 2021, the installed capacity of LFP accumulated 79.8 GWh, accounting for 51.7% of the total battery installed capacity, with a year-on-year increase of 227.4% [78]. By 2025, the estimated installed capacity of LFP in China is expected to reach 136 GWh, and the market share of LFP in the whole Chinese power battery market is expected to remain between 40% and 50%. Considering that the attitude of leading battery enterprises toward LFP has changed around the world, LFP is likely to have a broader market space. In short, LFP is about to usher in vigorous development from the mainstream choice in the early stage of industrial development, the rapid stage of industrial development, to the gradual maturity of the industry [79].

Tesla has replaced a large number of ternary lithium batteries with LPF. Tesla has ordered a 45 GWh LFP battery for the Model 3 and Model Y. The sales volume of models equipped with LFP batteries, such as BYD E-SEED GT EV and Agatsuma MINI EV, increased significantly. From the perspective of industrial layout, Chinese enterprises Ningde Times, BYD, GuoXuan High Tech, and other head battery enterprises are actively strengthening the construction of LFP battery capacity. Ningde Times and BYD have launched CTP and blade batteries based on LFP, respectively, which the market has recognized. GuoXuan High Tech has upgraded its LFP battery products and recently launched 210 Wh/kg LFP soft-packed cells and just-to-match (JTM) technology [79,80].

The continuous development and innovation of LFP batteries by enterprises have made up for the shortcomings of LFP batteries to a certain extent. BYD's "the blade battery" is a representative work of the Chinese enterprises' innovation in recent years. The blade batteries have changed the industry's dependence on ternary lithium batteries to a great extent, led the power battery restraint route to a new track, and redefined the safety standards of new energy vehicles.

According to the blade's shape, one can imagine that the blade battery is made longer and thinner than ordinary batteries, similar to the blade. Firstly, traditional battery packs are made of square or cylindrical batteries, but the blade battery is a combination of cells as thin as a blade. This way, the space layout in the battery pack can be optimized, and more cells can be arranged in the same volume, significantly improving the battery's energy density, and increasing the endurance mileage. The overall space utilization rate of the square battery is about 40%, and that of the blade battery can reach 60%. Secondly, the LFP battery has safety advantages compared to a ternary lithium battery. Now, after the square battery and cylindrical lithium iron phosphate battery become blade shaped, the safety of the battery is further improved. The reasons for the increased safety are that the short circuit of the blade battery is longer than that of a traditional battery, and the surface heat dissipation area is more significant than ordinary batteries. The acupuncture test is

an internationally used test to detect the safety of batteries. The acupuncture test showed that the ternary lithium battery will burn violently with an explosion, and the surface temperature will exceed 500 °C. The LFP battery with a square shape will smoke, but there will be no open fire and explosion, and the temperature will be between 200 and 400 degrees. However, the blade battery has no open flame, is smokeless, and the surface temperature is only 30 to 60 degrees, which makes the safety and stability jump to a new level. The blade battery solves the problem of spontaneous battery combustion to a great extent. Thirdly, blade batteries can skip modules when grouped through structural innovation, that is, no module design. Compared with the battery pack design with modules, the weight-specific energy density of blade batteries is 9% higher than that of battery packs with modules. The so-called module-free design aims to integrate the battery cells directly into a pack. As shown in Figure 6, the blade battery is arranged in an array to form a battery pack, reducing the module structure and the single connecting harness, improving the packaging efficiency, and increasing integration, called cell-to-pack technology [81].

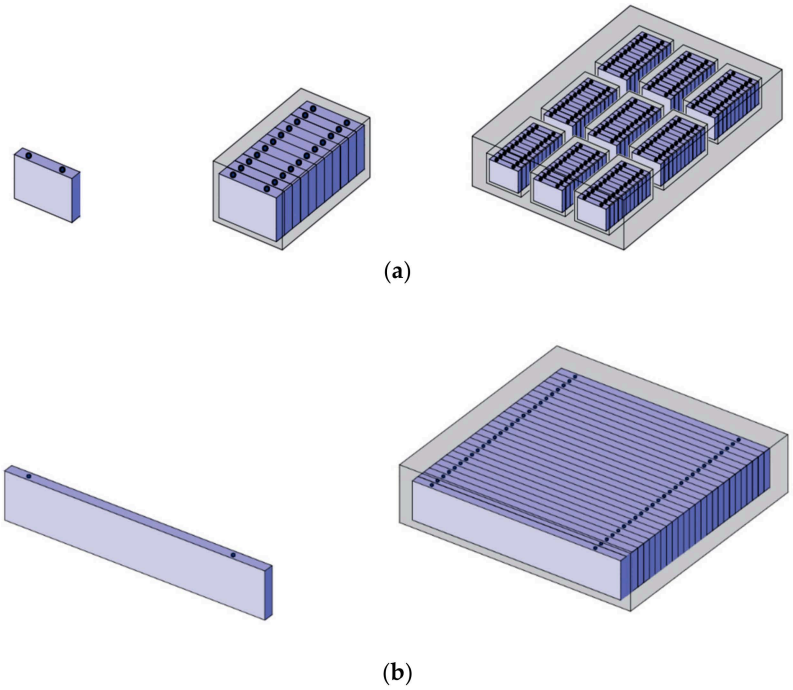


**Figure 6.** Cell-to-pack technology. (**a**) A schematic illustration of a conventional battery pack. (**b**) A schematic illustration of a blade battery pack. The conventional battery packs build batteries into modules first, then modules into battery packs. A blade battery pack builds on wide and short cells and assembles them directly into a pack. The blade battery pack has much higher mass and volume integration efficiencies. Referenced from [82].

Depending on the particularity of the blade battery shape and the stability of the material, the densely arranged blade batteries no longer need to be used as a standalone battery, and the space utilization rate has significantly improved. It also improves the feature that the LFP battery has too small an energy density per unit volume to a certain extent.

The authors of [82] evaluated the performance of the blade battery under various performance criteria required for EVs. They concluded that a blade-type LFP battery pack could deliver specific energy compared to an energy density even higher than a state-of-the-art ternary battery pack. Nevertheless, blade-type LFP batteries also have intractable shortcomings. For example, the output of blade batteries lacks diversity. The structure is as thin as a blade, and the characteristics of each cell as support make the blade battery challenging to repair after being impacted. It is more difficult to ensure the integrity of the battery. Finally, there is still no definite answer to whether the blade battery with LFP can

maintain its performance in the long-term low-temperature environment. The innovation for LFP is not limited to the blade battery.

It is worth mentioning that the blade battery does not limit the material selection to LFP. The ternary lithium battery can also make the structure of the blade battery, but because the safety of the ternary lithium battery is worse than the LFP battery, the technical application would be more difficult.

At the end of this section, according to the types of lithium-ion batteries described above, the specific applications of different lithium-ion batteries in commercializing EVs are summarized in Table 3.

In Table 3, the performance and operational state of lithium-ion power batteries are shown to be significantly influenced by typical driving cycles. Driving cycles refer to the combination of conditions, such as speed, acceleration, braking, and idling, experienced during actual vehicle use. These conditions directly affect the battery's charge–discharge behavior, temperature variations, lifespan degradation, and energy efficiency. For instance, frequent start–stop patterns in urban driving cycles can lead to repeated shallow charging and discharging of the battery, increasing internal resistance and reducing energy efficiency. Conversely, sustained high-power output in high-speed driving cycles may cause the battery temperature to rise, accelerating aging and even increasing the risk of thermal runaway. Additionally, low-temperature environments can reduce the battery's discharge capability, while high-temperature conditions may accelerate electrolyte decomposition and electrode material degradation. Deep discharging and high-load conditions can also hasten capacity degradation, and frequent charge–discharge cycles can accumulate aging effects, shortening the battery's lifespan. To enhance battery performance, intelligent energy management systems can dynamically adjust charge–discharge strategies based on driving cycles, while effective thermal management controls the battery temperature, thereby optimizing energy efficiency, extending the battery life, and ensuring the safety and reliability of electric vehicles.

Table 3 does not discuss power density, but it is closely related to the energy density discussed in Table 3. Energy density and power density are two key metrics describing battery performance. Energy density reflects the battery's ability to store energy, determining the device's runtime, while power density reflects the rate at which the battery can release energy, determining the device's power performance. The two are indirectly related through the factor of time, as power density can be expressed as energy density divided by discharge time. Therefore, for the same energy density, the shorter the discharge time, the higher the power density. However, the two cannot be directly converted, and battery design requires a trade-off between energy density and power density based on specific application needs.

In the context of electric vehicle power battery applications, electrode materials significantly impact the power density of batteries. When carbon is used as the anode material, the power density performance of different cathode materials is as follows: LMO typically exhibits a power density ranging from 500 to 1500 W/kg, making it suitable for high-rate discharge scenarios, although its energy density is relatively low. LCO has a power density of approximately 500 to 2000 W/kg, offering both high energy density and relatively high power density, but it suffers from poor thermal stability and higher costs. LFP has a relatively lower power density, around 200 to 1000 W/kg, but its excellent thermal stability, safety, and long cycle life make it an ideal choice for electric vehicles and energy storage systems. NMC has a power density ranging from 500 to 2500 W/kg, striking a balance between energy density and power density, and is currently the mainstream choice for electric vehicles. NCA can achieve a power density of 1000 to 3000 W/kg, offering extremely high energy density and relatively high power density, and is primarily used in

high-end electric vehicles, such as Tesla. Therefore, in the design of EV power batteries, it is necessary to balance energy density, power density, safety, cost, and cycle life based on specific requirements to select the most suitable cathode material.

**Table 3.** Overview of cells and batteries for different EVs. Source: data from [11,71].

| Cell Chemistry | | Cell Level | | | | Cell Pack Level | | Application Model and Manufacturer | |
|---|---|---|---|---|---|---|---|---|---|
| Anode | Cathode | Capacity (Ah) | Voltage (V) | Specific Energy (Wh/kg) | Energy Density (Wh/L) | Energy (kWh) | Driving Range (km) | Battery Manufacturer | Application Model |
| C | LCO | _ | 3.7–3.9 | 150–200 | _ | _ | _ | Sony (Tokyo, Japan) | _ |
| C | LMO–NMC | 50 | 3.7 | 109 | 218 | 16 | 160 | Li Energy Japan (Tokyo, Japan) | Mitsubishi i-MIEV (2008) |
| C | LMO-NCA-NMC | 60 | 3.7 | 122 | 228 | 22 | 130 | Samsung SDI (Yongin, Republic of Korea) | BMW i3 (2014) |
| C | LMO-NCA | 33 | 3.75 | 155 | 309 | 24 | 135 | AESC (Zama, Kanagawa, Japan) | Nissan Leaf (2010) |
| C | NMC | 52 | 3.65 | 152 | 316 | 17 | 145 | Li-Tec (Kamenz, Germany) | Smart Fortwo EV (2013) |
| C | NMC | 59 | 3.7 | 241 | 466 | 41 | 400 | LG Chem (Seoul, Republic of Korea) | Renault Zoe-2017 |
| C | NCA | 3.2 | 3.6 | 236 | 673 | 60–100 | 330–500 | Panasonic (Kadoma, Osaka, Japan) | Tesla S (2012) |
| C | LFP | 20 | 3.3 | 131 | 247 | 21 | 130 | A123 (Livonia, MI, USA) | Chevrolet Spark EV (2012) |
| C | LFP | 202 | 3.2 | 140 | _ | 64.8–76.9 | 506–605 | BYD (Shenzhen, Guangdong, China) | BYD7009BEV (2020) |
| LTO | NMC | 20 | 2.3 | 89 | 200 | 20 | 130 | Toshiba (Tokyo, Japan) | Honda Fit EV (2013) |
| Si–C or SiOx–C | NCA | 4.75 | 3.6 | 260 | 683 | 75–100 | 490–630 | Panasonic (Kadoma, Osaka, Japan) | Tesla 3 (2017) |
| C | NCM | 60 | 4.2 | 240–250 | 350–400 | - | 383 | LG Chem (Seoul, Republic of Korea) | Chevy Bolt (2018) |
| C | NCM | 90 | 4.2 | 240–260 | 350–400 | | 470 | LG Chem (Seoul, Republic of Korea) | Jaguar I-PACE (2019) |

**Table 3.** *Cont.*

| Cell Chemistry | | Cell Level | | | | Cell Pack Level | | Application Model and Manufacturer | |
|---|---|---|---|---|---|---|---|---|---|
| **Anode** | **Cathode** | **Capacity (Ah)** | **Voltage (V)** | **Specific Energy (Wh/kg)** | **Energy Density (Wh/L)** | **Energy (kWh)** | **Driving Range (km)** | **Battery Manufacturer** | **Application Model** |
| C | LFP | 76.9 | | 140 | 300–350 | | 506 | BYD (Shenzhen, Guangdong, China) | BYD Han (2020) |
| C | LFP | 202 | 3.2 | 140 | - | - | 405 | BYD (Shenzhen, Guangdong, China) | 2023e2 (2023) |
| C | LFP | 100–150 | - | - | - | - | 580 | CALB Group Co., Ltd. (Changzhou, Jiangsu, China) | Xiaopeng G6 (2023) |
| C | NCA | 4.8–5 | | 260–280 | 450–500 | | 652 | Panasonic (Kadoma, Osaka, Japan) | Tesla S (2023) |

In the table above, the year in the bracket indicates the start of production. C, graphite; Si, silicon.

LFP batteries and ternary lithium batteries are gradually replacing LCO and LMO batteries in electric vehicles for several reasons. Firstly, they offer higher safety, with LFP batteries exhibiting excellent thermal stability and being less prone to thermal runaway, while ternary lithium batteries strike a good balance between energy density and safety. Secondly, they are more cost-effective, as LFP batteries do not use expensive cobalt, and ternary lithium batteries reduce cobalt content through optimized formulations, making them more economical compared to LCO batteries. Thirdly, they have a longer lifespan, with LFP batteries significantly outperforming LCO and LMO batteries in cycle life, and ternary lithium batteries also offering relatively long lifespans. Lastly, they provide better energy density and performance, with ternary lithium batteries far exceeding LCO and LMO batteries in energy density, making them suitable for long-range applications, while LFP batteries excel in stability and cost-effectiveness. Therefore, LFP and ternary lithium batteries have become more ideal power battery choices for electric vehicles.

Based on the above discussion of the performance and prospects of current commercialized lithium-ion batteries, an attempt can be made here to summarize the comprehensive evaluation criteria for commercialized lithium-ion batteries. It can be mainly divided into five aspects, as follows:

(1) Driving range. Eliminating range anxiety is a problem that EVs have been addressing since they were first developed. Nowadays, the range of EVs has made significant progress, but there is still a particular gap compared with traditional fuel vehicles. Consumers are more willing to pay for EVs with long-range capabilities. High-end models are often willing to use the more expensive ternary lithium battery because the ternary lithium battery has an advantage in driving range. The driving range is undoubtedly one of commercial lithium-ion batteries' most crucial evaluation metrics.

(2) Cost. Reducing the cost is undoubtedly an essential part of the commercial battery. Ternary lithium batteries, widely used in EVs today, are expensive because they rely on cobalt metal. The volatility of lithium prices will also significantly affect the EV market. For example, reducing the dependence on scarce metal resources, developing

cobalt-free lithium-free batteries, and reducing the cost of battery packs are the keys to developing EV batteries.

(3) Stability. Stability here refers to the ability of the battery to be affected by the environment without changing its performance. EV batteries are susceptible to environmental impact, a label many consumers put on them. It is also true that the performance of EV batteries in commercial use today is affected by temperature changes, especially when the temperature is significantly reduced. Among them, LFP batteries and LMO batteries are most significantly affected. For example, a traditional LMO battery can operate safely at 55 °C, but the battery capacity will drop to 75% of the initial capacity [83]. Better stability can significantly improve the competitiveness of EVs.

(4) Security. There are still significantly more safety incidents reported for EVs than for gasoline vehicles. The most concerning is the explosion of the battery under severe impact. How to integrate the battery of an EV to improve its impact resistance and at the same time make the battery pack have enough energy density to ensure endurance is a problem that needs to be deeply studied.

(5) Life. Battery life includes calendar life and cycle life. Different batteries have different lives according to different cathode materials and different manufacturing processes [84]. The calendar life of commercial batteries is 10–15 years, and the cycle life of LFP batteries can reach more than 3000 times, while the ternary lithium battery is about 2000 times. A higher lifetime means that EVs can be used for more years, which needs further improvement.

(6) Charging speed. EVs should be able to replenish more power quickly. The charging speed significantly affects the experience of using EVs. More and more car companies are paying attention to fast charging technology, such as Tesla's supercharger. The innovation of charging speed is an essential direction for the development of EV batteries in the future.

## 4. Prospect of Lithium Battery for EVs

### *4.1. Prospect of Lithium-Ion Battery*

Although lithium-ion batteries have many competitors, they still dominate the market due to the rapid upgrade of the technique. In the future, the range target of EVs would be more than 500 km. High range requires the specific density of the battery to reach about 230 Wh/kg and the energy density of the battery to reach about 500 Wh/L. Industrialized lithium-ion batteries can only meet around half of these numbers [85,86].

The researchers have further improved the performance of lithium-ion batteries through the following aspects. On the one hand, they are adopting new materials, including new high-capacity cathodes and anodes and new electrolytes to enhance the cell configuration. For example, $Li_5FeO_4$, LTO cathodes, and Si-based anodes can reduce the electrode material size and enhance ionic and electronic conductivity [87]. The low volumetric structures can accommodate the volume changes during lithium transferring in and pulling out [7]. The Tesla 4680 cell mentioned in the previous section implements higher Si content in high-energy anodes, achieving remarkable results. On the other hand, some attempts have been carried out to improve the battery structure, including the innovation of single battery and battery pack structures. The 4680 cell is a progressive innovation of the single battery, while the blade battery has changed the integration of the single battery to the battery pack. Both of them have made good performance progress.

A promising alternative for future electric vehicles is the pouch-type lithium-ion battery. Unlike traditional lithium-ion batteries, which typically feature cylindrical or rectangular shapes with heavy iron or aluminum casings, pouch batteries utilize lightweight aluminum–plastic composite materials for their outer packaging. This design not only

reduces the overall weight of the battery but also enhances its specific energy and safety. The flexible nature of the pouch design minimizes the risk of explosions caused by gas expansion during misuse, a common issue with rigid-shell batteries. The manufacturing process of pouch batteries involves several steps, including electrode cutting and trimming, stacking, tab welding, encapsulation, electrolyte injection, molding, and degassing, followed by re-encapsulation [88,89].

To produce a pouch battery, the positive and negative electrodes, along with the separator, are first cut from roll materials. The initial assembly step involves welding metal tabs to the current collectors. The electrode stack is then placed into the pouch, followed by the injection of liquid electrolytes. Finally, the battery is vacuum-sealed to complete the fabrication process [90].

Pouch batteries offer significant advantages in terms of energy density and weight reduction. They can store more energy within a given physical space compared to cylindrical or rectangular batteries, making them highly suitable for EVs, where space is limited. Additionally, pouch batteries are lighter than their cylindrical and rectangular counterparts of similar size, contributing to a reduction in the overall weight of the vehicle. However, one challenge with pouch batteries is their difficulty in stacking compared to traditional rigid-shaped batteries [91].

Pouch batteries hold a significant position in electric vehicle power batteries due to their high energy density, lightweight design, and flexibility, making them particularly suitable for high-end models, though their mechanical strength and thermal management complexity still need improvement. Cylindrical batteries, on the other hand, excel in mature technology, excellent heat dissipation, and low cost. Despite their lower space utilization, the introduction of large-format cylindrical batteries (such as the 4680) has injected new momentum into their development. Blade batteries stand out with their unique structural design and high safety (based on LFP chemistry), offering high space utilization and superior structural strength, though their complex manufacturing process and energy density limitations (due to the LFP system) remain challenges. Overall, pouch batteries are suited for the high-end market, cylindrical batteries have advantages in mid-to-low-end and energy storage applications, and blade batteries excel in safety and space utilization. Together, these three technologies drive the diversified development of electric vehicle power battery technology.

### *4.2. Lithium-Metal Technologies*

Due to the limitations of traditional lithium-ion batteries in terms of safety and specific energy, many researchers hope to develop new high-energy-density and high-safety lithium power batteries, including lithium/air (Li-$O_2$) batteries, lithium/sulfur batteries, and solid-state batteries.

The Li-$O_2$ battery uses metal-lithium as the negative electrode, oxygen in the air as the positive electrode, and water, organic electrolytes, or solid electrolytes as the electrolytes. Currently, the electrolytes used in Li-$O_2$ batteries are mainly divided into aqueous and non-aqueous. Li-$O_2$ batteries with non-aqueous electrolytes can theoretically reach extremely high specific energy (~11,700 Wh/kg), thus being competitive with traditional gasoline [92,93]. By reacting lithium directly with oxygen from the air, according to the reaction $2Li + O_2 \rightleftarrows Li_2O_2$, a very high capacity of 1200 mAh/g may be obtained, a much greater value than that possibly achievable by any insertion cathode [20]. Researchers are searching for probable approaches to improve the round-trip efficiency and cycle life of Li-$O_2$ batteries, especially for electrode protection [94]. However, the development of lithium-air batteries still faces significant challenges, for example, stability and safety of electrolytes and corrosion of the lithium-metal negative electrode and lithium dendrite [95].

Lithium-sulfur batteries with sulfur as the cathode are known for their extremely high energy density, which reaches 2600 Wh/kg. The operating voltage of lithium-sulfur batteries is low, at 2.2 V, but the high theoretical capacity of elemental sulfur can make up for this shortcoming [96]. In addition, elemental sulfur exists in large quantities in nature, and the cost of obtaining it is relatively low, which makes large-scale application of lithium-sulfur batteries a possibility. However, the shuttle effect of lithium-sulfur batteries is an important factor restricting their development. The shuttle effect is mainly caused by the dissolution of polysulfides in organic liquid dielectrics. With the solid-state sulfur discharge for high-order polysulfide, it will dissolve into the electrolyte, and with the anode of the lithium reaction to form low-order polysulfide, low-order polysulfide will diffuse back to the cathode and in the charging to generate high-order polysulfide. The polysulfide will diffuse back and forth between the cathode and anode, a phenomenon known as the shuttle effect. This leads to poor cycle stability and severe anode corrosion in lithium-sulfur batteries. Currently, according to the migration path of polysulfides, methods to inhibit the shuttle effect of polysulfides in lithium-sulfur batteries are classified into five categories: (1) avoiding the formation of long-chain polysulfides, (2) immobilizing polysulfides within the sulfur body, (3) reducing the solubility of polysulfides in the electrolyte, (4) preventing polysulfides from passing through the diaphragm, and (5) inhibiting the chemical reaction between the polysulfides and the lithium anode [97]. In addition to the shuttle effect, lithium-sulfur batteries have other problems, including uneven deposition of lithium ions that can lead to lithium dendrites, and the problem of volume change of active materials during charging/discharging.

Solid-state batteries featuring a lithium-metal anode are considered the most promising next-generation batteries for commercialization due to their enhanced energy density and improved safety. By replacing liquid organic electrolytes with solid electrolytes, solid-state batteries address the challenges of energy density, lifespan, and safety that conventional lithium-ion batteries encounter. These batteries represent the future direction of high-capacity secondary batteries and are ideal for electric vehicles and large-scale energy storage systems [98]. Compared to traditional liquid lithium-ion batteries, all-solid-state lithium-ion batteries offer several advantages. Firstly, they eliminate risks, such as leakage and corrosion, associated with liquid electrolytes, while also exhibiting superior thermal stability. Additionally, solid-state batteries enable internal series connections, allowing for higher output voltages and compatibility with high-voltage cathode materials [99].

Lithium battery technology is expected to advance rapidly in the coming years. At the 2022 China EV100 conference, Ouyang Minggao forecasted that the energy density of liquid-based lithium batteries would reach 350 Wh/kg by 2025, with semi-solid systems gradually being developed [100]. By 2035, all-solid-state systems with energy densities of 500 Wh/kg may become a reality, alongside the commercialization of advanced batteries, such as lithium-sulfur and lithium-air. Furthermore, non-lithium alternatives, like sodium-ion and potassium-ion batteries, also show significant potential [101]. Figure 7 illustrates the projected evolution of battery technology. As depicted, while lithium-ion batteries still have room for improvement, they are approaching their performance limits. Emerging technologies, including solid-state, lithium-sulfur, and sodium-ion batteries, are expected to dominate future commercialization efforts.

At the same time, lithium battery technology still faces many challenges, which can be summarized as follows.

It is susceptible to environmental conditions. Under adverse conditions, such as high temperature, low temperature, and temperature differences of the battery pack, EV performance will be affected to different degrees.

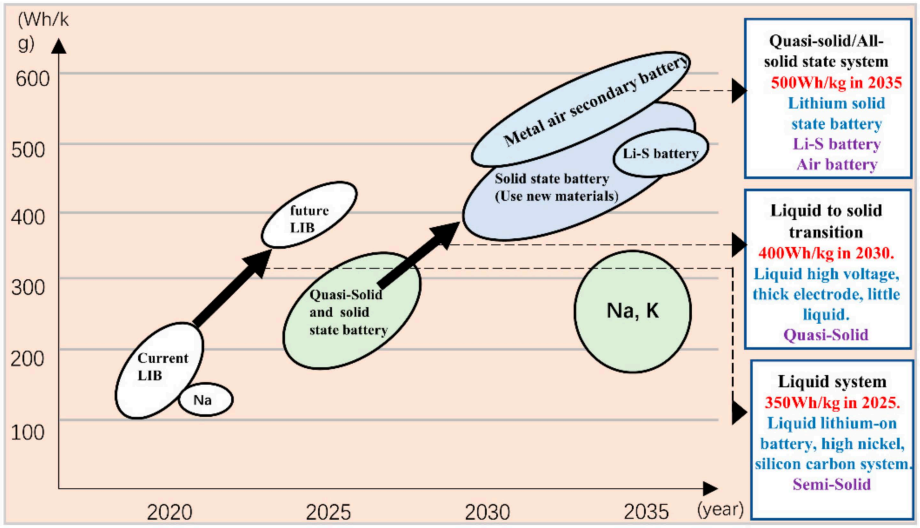



**Figure 7.** Battery development trend. Refer to the speech of academician Ouyang Minggao at the China EV100 conference in March 2022 [101] (LIB, lithium-ion battery; Li-S, lithium-sulfur; Na, sodium-ion battery; K, potassium-ion battery).

At low temperatures, the battery performance will show a significant degradation. Further, the battery's charging acceptance, energy, and power will be affected. Charging a lithium-ion battery at low temperatures makes it difficult to charge it to room-temperature capacity, and lithium plating may occur at high charging rates [102]. At −40 °C, the power and energy density of the lithium-ion battery can only reach 1.25% and 5%, respectively, compared to 20 °C. In addition to worse performance, low temperatures also affect the life of lithium-ion batteries, with an 11.5 Ah lithium-ion battery losing 25% of its capacity after only 40 cycles at a charge rate of 0.5 C at −10 °C [103].

At high temperatures, the performance of the battery is adversely affected by capacity/power attenuation and self-discharge. Generally, capacity degradation is due to lithium depletion and reduction of active material inside the battery, and power degradation is due to increased internal resistance due to elevated temperatures. For the self-discharge rate, an elevated temperature increases electronic conductivity, which increases the self-discharge rate of the negative electrode [104,105].

The Sony 18,650 battery lost 36% of its capacity after 800 cycles at 45 °C [106]. The lithium-ion battery power decay was 55% during 20 weeks of storage at 55 °C [107]. In addition to poor performance at high temperatures, the battery module is prone to overheating due to short circuits and high ambient temperature, efficiently producing unacceptable safety problems [108].

In addition to low- and high-temperature performance, uniform temperature distribution is essential for proper battery operation. Usually, a battery pack is composed of multiple single cells, and there will be some differences in resistance, capacity, and other aspects between each cell. These differences can lead to non-uniform temperature distribution in the battery pack [109]. A temperature difference of only 5 °C can lead to a 10% decrease in power capability. Moreover, such temperature inhomogeneity may lead to thermal runaway and catastrophic failure of the battery [108].

The main raw materials of lithium-ion batteries, such as lithium, cobalt, nickel, manganese, and graphite, are unevenly distributed, and their extraction processes significantly impact the environment and resource consumption. Battery production is energy-intensive, with high carbon emissions and the potential generation of hazardous waste. During the usage phase, carbon emissions are relatively low, but the battery's lifespan and efficiency directly affect its overall environmental impact. If not properly managed at the end-of-life

stage, heavy metals and electrolyte pollution can harm ecosystems and human health. Regarding different anode materials, the environmental impact of graphite anodes is primarily concentrated in the extraction and production processes. Silicon-based anodes offer high capacity but suffer from short lifespans, while lithium titanate (LTO) anodes have long lifespans but high production costs. To enhance sustainability, it is recommended to strengthen research on recycling technologies, promote secondary use, develop new materials (such as silicon-based and LTO anodes), and support policies that encourage battery recycling and cascading use. By integrating these measures, the environmental impact of lithium-ion batteries can be reduced, supporting the transition to green energy [110].

In addition to the challenges of environmental impacts on lithium-ion batteries, some aspects, such as those mentioned in Section 3, are also ones that lithium-ion batteries need to address in the future:

(1) The driving range still needs to be improved. Although the range of existing commercial lithium batteries has made significant progress, it still needs further improvement.
(2) Fast charging capacity of the battery. How to complete the fast charging of most of the battery in a short time is an excellent challenge for battery researchers.
(3) The cost of battery packs still needs to be reduced. We can control the cost of producing battery packs from several aspects: material selection, design, manufacturing, waste battery pack recycling, and battery pack supply chain.
(4) Reduce dependence on scarce resources. In the future, developing lithium- and cobalt-free batteries may be a development challenge and direction of power batteries.

## 5. Conclusions and Prospects

In this paper, the commercial application of lithium-ion batteries has been inspected in detail. Lithium-ion battery materials can be divided into LCO, LMO, NMC, NCA, and LFP according to the different cathode materials. Because LCO has shortcomings in safety, cost, and cycle life, few EVs choose to use it alone, and it is close to being eliminated in the field of EVs. The stability of LMO is better than LCO, and its attractive cost advantages have led some researchers and companies to continue to work on LMO batteries in the hope that they will have a chance to be used in future mainstream EVs. Ternary lithium batteries are known for their high energy density and driving range, making them the first choice for many high-end models. Before the emergence of LFP batteries, ternary lithium batteries were the absolutely main characters in EVs. However, the safety of ternary lithium batteries is not great, so they have become the protagonists of many EV battery spontaneous combustion incidents. Tesla chose to use the 18,650 batteries with mature packaging technology and high safety, but the small-cell battery has an excellent test for the battery management system. Larger batteries tend to overheat. In response to these problems, Tesla has also made innovations in the battery structure. The design of the infinity lug of the 4680 cells reduces the accumulation of battery heat so that the battery can adopt a more significant charging current and improve its charging efficiency. LFP batteries, which are safe and do not contain expensive cobalt, have gained momentum in recent years. Many of the world's leading car companies are already considering using LFP batteries, which makes it a broad market space. Although LFP batteries are slightly inferior in terms of energy density, researchers' innovations in battery architecture have primarily compensated for these shortcomings. For example, in the blade battery, by optimizing the spatial layout in the battery pack, more cells can be placed in the same volume, which indirectly improves the energy density of the battery.

After discussing the current commercial application of lithium-ion batteries, this paper further discussed some cutting-edge technologies of lithium-ion batteries, including electrolyte technology, high-energy-density in situ polymerization technology, and pouch

batteries. Although the existing lithium-ion battery technology has achieved the popularization of EVs, many pain points still limit the further development of EVs. For example, the driving range of EVs is significantly affected by temperature and vehicle energy consumption, which makes the actual driving range low. The problem of long charging time has yet to be fundamentally solved, and sometimes it is challenging to meet users' needs. In addition, the annual increase in the price of lithium carbonate also challenges the cost of lithium-ion batteries. In order to further develop lithium-ion batteries, structural innovations, such as the blade battery and the 4680 cells, need to be continued, and bag-shaped batteries are a possible direction. The development of electrolyte technology can also enhance the performance of batteries, such as in situ polymerization technology.

To meet consumer expectations for EVs, the battery pack power of EVs needs to be increased by more than 25% on the basis of the same volume and weight. In terms of charging speed, the battery life needs to be more than 400 km every ten minutes. It is of interest to reduce the cost of the battery pack to less than USD 100 per KWh. At the same time, it is also impotant to reduce the dependence on cobalt metal, lithium metal, and other rare metals.

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## Abbreviations

| | |
|---|---|
| EVs | Electric vehicles |
| Ni-Cd | Nickel-cadmium |
| Ni-Zn | Nickel-zinc |
| Ni-$H_2$ | Nickel-hydrogen |
| LMO | Lithium manganese oxide |
| NCA | Lithium nickel cobalt aluminum oxide |
| LTO | Lithium titanate |
| JTM | Just-to-match |
| EC | Ethylene carbonate |
| EMC | Ethyl methyl carbonate |
| PC | Propylene carbonate |
| ISEs | Inorganic solid electrolytes |
| SPEs | Solid polymer electrolytes |
| HEVs | Hybrid electric vehicles |
| FCEVs | Fuel cell electric vehicles |
| BEVs | Battery electric vehicles |
| Ni-Fe | Nickel-iron |
| Ni-Mn | Nickel-manganese |
| LCO | Lithium cobalt oxide |
| LFP | Lithium iron phosphate |

| | |
|---|---|
| NMC | Lithium nickel manganese cobalt oxide |
| Si | Silicon |
| ROW | Rest of the world |
| DMC | Dimethyl carbonate |
| DEC | Diethyl carbonate |
| SEI | Solid electrolyte interphase |
| PEs | Polymer electrolytes |
| CPEs | Composite polymer electrolytes |

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