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Status and Development of Power Lithium-Ion Battery and Its Key Materials

1.1 Market Status of Power Lithium-Ion Battery

Lithium-ion batteries (LIBs) were invented by Sony in 1990 and brought to the market for commercialization in 1991, which kicked off the rapid development of LIBs. Initially (before 2000), most of the world's lithium batteries were produced in Japan [1–3]. However, by the year of 1997, South Korea's lithium secondary battery market began to rise, and it once surpassed Japan in the field of portable mobile electronics. In 1996, China Electronics Technology Group successfully developed 18650 batteries that can be mass-produced, marking the start of China's lithium batteries industry. At present, as an advanced energy storage technology, power LIBs have been widely used in new energy electric vehicles, providing critical support for the current greenhouse gas emission reduction.

According to the International Energy Agency (IEA), there was 16.5 million electric vehicles in the world by the end of 2021. The electric car registrations and sales share in major countries and regions in the world from 2016 to 2021 were shown in Figure 1.1. It is estimated that the total number of electric vehicles in the world will reach about 200 million by 2030, accounting for 20% of the total number of vehicles worldwide. The booming development of electric vehicles will lead to an exponential increase in the demand for power LIBs.

According to SNE Research data, the global installed capacity of power LIBs will be approximately 296.8 GWh in 2021 with a yearly increase of 115%. In view of the huge market prospects of the lithium-ion power battery industry [4], the relevant companies from different countries have deployed the power battery industry development plans. Among the world's top 10 battery companies (Figure 1.2), five of them are from China, namely Contemporary Amperex Technology Co., Ltd. (CATL), Build Your Dreams (BYD), China Aviation Lithium Battery (CALB), Guoxuan High-tech (GOTION), and Envision AESC with a total market share of 47.6%; LG Chem (LGC), Samsung SDI, and SKI, located in Korea, have a total market share of 30.4%; and Panasonic's (Japan) global market share is 12.2%.

Based on the ground of national level, the current lithium-ion power battery industry has basically developed into "three-legged (China, Japan, and South Korea)

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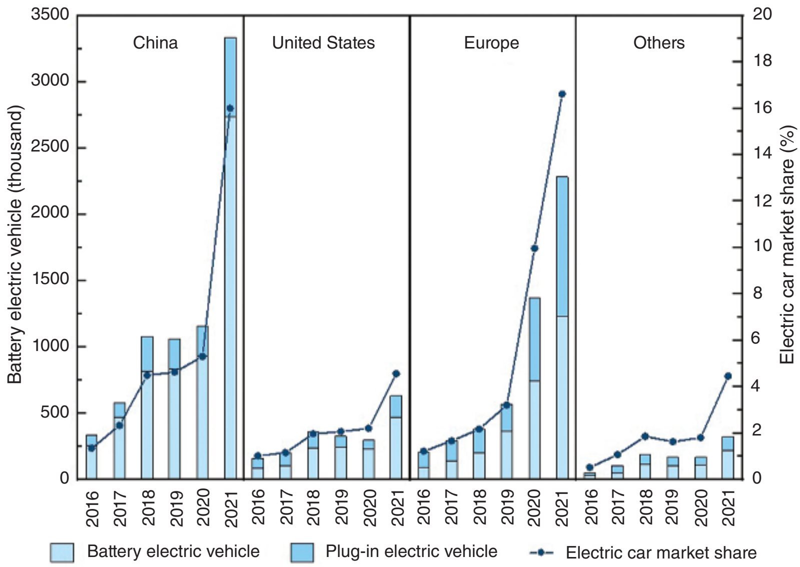

Figure 1.1 Registration volume and market share of electric cars in major countries and regions in the world, 2016-2021. *Source:* IEA.

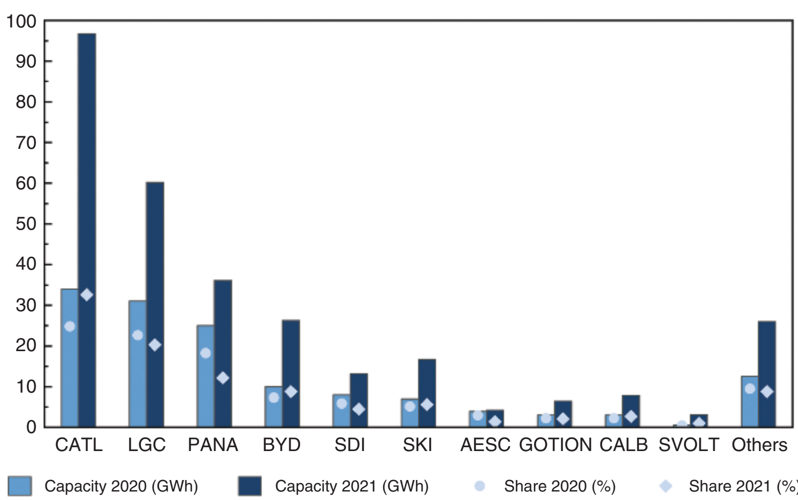

Figure 1.2 Top 10 global lithium-ion power battery companies and their installed capacity.

stand-up" pattern, and each of them has a leading enterprise in the industry. The Chinese company CATL has become not only the leader of China's lithium battery industry but also the world's largest supplier of power LIBs since 2017 [5] and was the first company to realize the mass production of NCM811 square batteries, which were successfully selected by GAC and BMW. From the technical route point of view, CATL also successfully realized the transition from NCM523 to NCM811.

Table 1.1 The main material production capacity of the world's major producers of lithium batteries.

	Cathode material	Anode material	Electrolyte	Separator
Country	**3000 kilotons**	**1200 kilotons**	**339 kilotons**	**1987 million m^2**
China	42%	65%	65%	43%
Japan	33%	19%	12%	21%
Korea	15%	6%	4%	28%
US	—	10%	2%	6%
Other	10%	—	17%	2%

Source: Data from Eddy et al. [7].

For South Korea's companies, LGC began to study lithium batteries in 1996 [6], and in 2020, it became the sole supplier of GM Chevrolet Volt electric vehicles. LGC's advantage is its advanced theoretical technology on soft pack batteries. It is also the first company in the world to be proficient in laminated-stacked soft packs. However, in the application of NCM811, it is behind the CATL. The Japanese company Panasonic began to develop the lithium batteries as early as 1994 and was supported by the Sumitomo Consortium. In 2008, it began to cooperate with Tesla, the world's largest electric vehicle company and built a super battery factory in 2014. Panasonic is the first company worldwide to realize the mass production of NCA18650 + silicon carbon anode cylindrical batteries, and it is also in a leading position in terms of the electrochemical system, production yield, and consistency.

In addition, China has already set up a strong leading position in the manufacturing of key materials for power LIBs (Table 1.1). According to the report "The metal mining constraints on the electric mobility horizon," China's production capacity in cathode materials, anode materials, electrolytes, and separators is 42%, 65%, 65%, and 43% of the world's total production capacity, respectively, far ahead of other countries and regions. Japan, by contrast, has a minor advantage in manufacturing cathode materials, whereas South Korea has an advantage in manufacturing diaphragms. In addition, other countries and regions such as the United States and the European Union have a relatively small market share in the production and manufacturing of materials for powered lithium batteries. The report shows that the market space for battery production and manufacturing in Western countries still has the great potential.

1.2 Key Materials and Development of Power Battery

Power LIBs are mainly composed of cathode materials, anode materials, separators, electrolyte binders, and current collectors. The cathode materials account for more than 40% of the total cost of lithium batteries, whose properties directly affect a variety of performance indicators of lithium batteries. Therefore, the cathode materials take a core position in lithium batteries industry [7, 8]. Currently, commercialized cathode materials for lithium batteries include lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), and ternary materials. The proportion of LFP and ternary materials is as high as 90% in all the cathode materials.

1.2.1 Dominant Cathode Materials

1.2.1.1 Lithium Nickel Cobalt Manganese Oxide

The molecular formula of the lithium nickel cobalt manganese oxide (NCM) oxide ternary cathode material is $LiNi_aCo_bMn_cO_2$, where $a + b + c = 1$. The naming rule of specific materials is usually based on the relative content of the three elements, for example, $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ is referred to as NCM811 for short. The different proportions of the three elements endow the NCM cathode material with different properties, which can meet the needs of diversified applications. NCM material combines the advantages of three types of materials as follows: LCO, lithium nickel oxide (LNO), and LMO. By adjusting the ratio of transition metal elements, the performance of the cathode material can be effectively regulated, and the cost of the cathode material can be reduced. Among them, the Ni element is beneficial to the increase of the specific capacity of the cathode material, which, however, is harmful to its thermal stability [9]; the Co element is beneficial to improve the electrical conductivity and rate performance of the material, but it is expensive; the presence of Mn plays a role in stabilizing the crystal structure of the polycrystalline, but it will also reduce the specific capacity of the cathode material when an excessive content was used.

The main preparation methods of NCM cathode materials include high-temperature solid-phase, sol–gel, co-precipitation, hydrothermal synthesis, and other methods. At present, commercial NCM materials were generally prepared with NCM hydroxide by precipitation method. The NCM precursor is mixed with a lithium source and calcined to prepare a finished NCM cathode material. The production of NCM precursor generally adopts the hydroxide co-precipitation method, that is, the mixed salt solution of nickel, cobalt, and manganese, precipitating agent, complexing agent, etc., are added to the reactor at the same time, and the NCM precursor is synthesized under specific conditions. The internal structure of the reactor and the control of the synthesis process are very demanding. Therefore, it takes an important position in the industry chain and has a high technical barrier. However, it has an important impact on the quality of the NCM cathode material. From the practical application point of view, the characteristics of the material particles, such as the morphology, particle size distribution, specific surface area, and tap density, have a great influence on the processing performance of battery electrode and the core electrochemical performance of lithium battery, such as energy density, rate performance, and cycle life. Therefore, the spherical NCM cathode material with high density and uniform particle size distribution has become the current pursuit goal of industry.

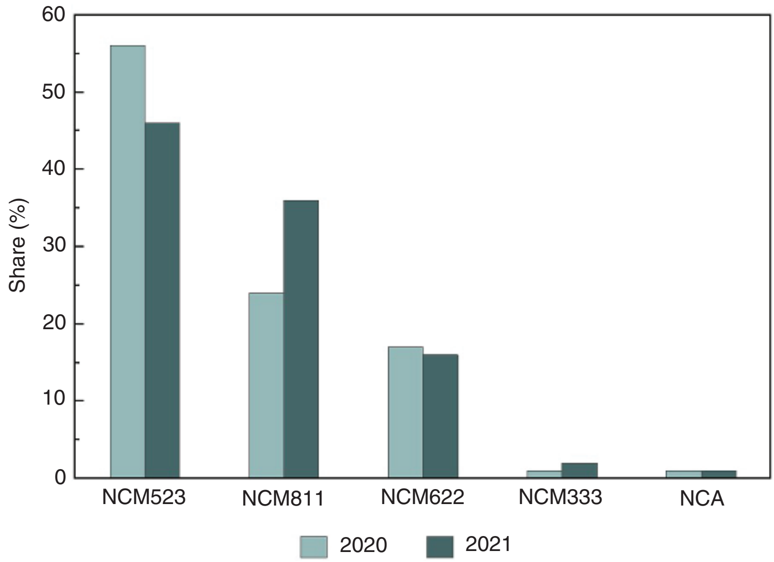

Figure 1.3 Comparison of the product structure of China's NCM materials in 2020 and 2021. *Source:* SMM.

Shanghai Metals Market (SMM) analysis of the results based on the output structure shows that, although the NCM material is still mainly NCM523, the trend of using low cobalt and high nickel is very clear. The proportion of NCM811 increased from 24% to 36% in 2021 (Figure 1.3). According to China Powder Network, GEM has developed an NCM precursor material with a molar ratio of nickel metal higher than 90% and has built an NCM precursor production capacity of 100 000 tons/yr. Sales volume of the high nickel and single crystals account for more than 80% of total sales. SKI, another power battery giant in South Korea, is earlier in the layout of ultra-high-nickel batteries and plans to launch a new NCM battery before the end of 2021. The battery has a nickel content of 88% and a cobalt content of 6%. Another South Korean company, LGC, plans to release lithium nickel cobalt manganese aluminum oxide (NCMA) batteries in 2022, with the 90% nickel content, 5% cobalt, and 1–2% manganese and aluminum.

1.2.1.2 Lithium Nickel Cobalt Aluminum Oxide

The lithium nickel cobalt aluminum oxide (NCA) material is composed of three main elements of nickel, cobalt, and aluminum, and the molar ratio is usually 8 : 1.5 : 0.5. By combining $LiNiO_2$ and $LiCoO_2$, not only the reversible capacity becomes high, but the cost also becomes low. Currently, doping Al into metal oxide and replacing manganese with Al (transition metal) are one of the most popular directions in commercial cathode materials. At present, high-nickel materials can be divided into two categories: NCM811 and NCA materials. The reversible capacity of both materials can reach about 190–200 mAh/g. However, because Al is an amphoteric metal, it is not easy to precipitate, and the conventional precipitation method cannot be used to prepare the NCA precursor. The NCA sintering process requires a pure oxygen atmosphere, which requires not only high tightness of the production equipment but also the oxidation resistance of the internal components of the kiln equipment. Due to the above-mentioned requirements of mass production, there are certain thresholds in the manufacturing process of NCA materials. In terms of route selection, Japan is mainly based on NCA routes, while South Korea tries to let NCM and NCA routes go hand in hand. China's current NCA output is relatively small, and NCM routes are the mainstay.

At present, the most mainstream preparation method is as follows: the precipitation of nickel, cobalt, and aluminum hydroxide is first prepared with metal sulfate as the raw material and sodium hydroxide or a complexing agent as the precipitation agent. The precipitate formed is then mixed with lithium hydroxide and then calcined into an oxide product. The advantages of this process are low production cost, simple process, and suitable for large-scale production. For example, Japan's Sumitomo and Japan's Toda have entered the mass production stage. Internationally, the upstream and downstream of NCA have formed a complementary industrial chain and a relatively stable and mature supply chain. However, China's domestic market is still at the initial stage of development.

1.2.1.3 Lithium Iron Phosphate

The chemical formula of LFP is $LiFePO_4$, and its theoretical specific capacity is 170 mAh/g. The actual specific capacity of the product can exceed 160 mAh/g (0.2 C, about 25 °C, the voltage platform is 3.2–3.5 V, and the tap density is 1.2 g/cm^3). In the $LiFePO_4$ structure, there is a strong covalent bond between O and P to form a tetrahedral $(PO_4)^{3-}$polyanion; hence, O is difficult to deintercalated, and no oxygen escapes after overcharge. When $LiFePO_4$ is used as a cathode electrode material, battery safety can be promised.

Solid-phase synthesis is the most widely used and most mature synthetic method for LFP production. The iron source used in this method is generally ferrous oxalate, iron oxide, iron phosphate, etc.; the lithium source is generally lithium carbonate, lithium hydroxide, lithium acetate, etc.; and the phosphorus source is generally ammonium dihydrogen phosphate and diammonium hydrogen phosphate. The disadvantage of the solid-phase synthesis method is that it is easy to produce ammonia that pollutes the environment. Representative manufacturers include A123 systems, Tianjin Strand, Hunan Rui Xiang, Peking University First, Defang Nano, etc. At present, most of the synthesis method in our country adopts the ferrophosphorus process. This process generally uses iron phosphate as the iron source, which is first mixed with the lithium source at the nanoscale. After that, the particles can be converted into high-quality LFP materials with controllable particle size by spray drying and calcination in nitrogen atmosphere. Representative manufacturers include Phostech in Canada, Shandong Feng Yuan Lineng Technology Co., Ltd., and Sichuan Yuneng New Energy Battery Materials Co., Ltd.

The emergence of LFP is a breakthrough in LIB cathode materials. The following advantages of LFP, such as low price, environmental friendliness, high

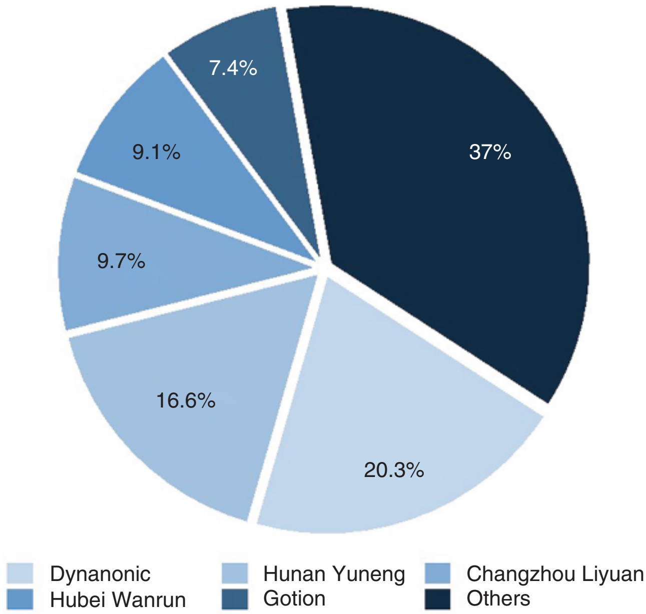

Figure 1.4 Market share of LFP manufacturers in 2021. *Source:* GGII.

safety performance, better structural stability, and cycle performance, have prompted it to have a wider market application field: Energy storage equipment, power tools, light electric vehicles, large electric vehicles, small equipment, and mobile power sources, among which, the LFP for new energy electric vehicles accounts for about 45% of its total production. The market share of LFP in China is displayed in Figure 1.4. Due to the structural reorganization of LFP batteries, the increase in energy density, the decline of new energy vehicle subsidies, the popularization of charging piles, the price advantage, and high safety advantages of LFP batteries, the installed capacity of LFP batteries in China has rapidly increased. Thus, the shipment of LFP cathode materials in China has been 470 000 tons by 2021, accounting for a year-on-year increase of 277%, according to the survey data of the Advanced Industrial Research Institute of Lithium Battery Research (hereinafter referred to as GGII).

1.2.1.4 Lithium Nickel Manganese Oxide

The molecular formula of lithium nickel manganese oxide (LNM) is $LiNi_{0.5}Mn_{1.5}O_4$, which belongs to the spinel structure. The voltage platform is about 4.7 V, the theoretical specific capacity is 146.7 mAh/g, and the actual specific capacity is about 130 mAh/g; LNM has a high working voltage, high energy density, and low production cost. It combines the advantages of NCM materials and LFP materials, which is the goal of a new generation of cathode materials.

There are many preparation methods for LNM, including solid phase, co-precipitation, sol–gel, solution combustion synthesis, hydrothermal, solvothermal, and spray deposition methods. Public information shows that Honeycomb Energy mainly improves the performance of LNM through three methods: cation doping, single crystal technology, and nano-network coating. Doping technology involves the use of cations with high chemical bond energy with oxygen to dope into the crystal structure, which is conducive to the stability of the structure after de-lithiation under high voltage. Single crystal technology has a higher particle strength than traditional spherical polycrystalline particles, which is beneficial to improve safety and cycling performance. The use of a nano-network coating can make the material more uniform and reduce the side reaction with the electrolyte to improve the cycle life.

Reducing the cobalt content has become the primary measure for reducing the cost of NCA or NCM cathode materials, and the development of high-nickel and cobalt-free materials has become an inevitable trend. Tesla has always used the ternary battery (NCA) provided by Panasonic, in which the Co content is less than 3%, and the next generation of products can reduce the content of Co to zero. Since then, cobalt-free batteries and cobalt-free materials were born. According to Gaogong Lithium Grid, Honeycomb Energy's Changzhou plant has officially mass-produced cobalt-free materials, with an annual output of up to 5000 tons. Mine Road Network speculates that, by 2025, the global production of LNM oxide materials will reach 85 000 tons, and the demand will reach 100 000 tons. If LNM solves the problems of large-scale production and high-potential electrolyte tolerance, it will surely become the next generation of mainstream cathode materials.

1.2.2 Anode Materials

The negative electrode material is the main body that stores lithium when the power battery is charged, accounting for about 10% of the battery cost. Anode materials can generally be divided into two categories: carbon materials and noncarbon materials. Carbon materials include artificial graphite, natural graphite, mesophase carbon microspheres, petroleum coke, carbon fiber, and pyrolytic resin carbon. Noncarbon materials include titanium-based materials, silicon-based materials, tin-based materials, and nitrides.

1.2.2.1 Graphite

Since graphite materials have the advantages of high electronic conductivity, high specific capacity, stable structure, and low cost, they have become the most widely used and mature anode materials, and they are the absolute mainstream route in the anode industry, accounting for 95% of the total amount. Graphite can be divided into natural graphite and artificial graphite. Due to raw material and process characteristics, the internal structure of artificial graphite anode materials is more stable than natural graphite products.

Artificial graphite is generally divided into four major processes, namely crushing, granulation, graphitization, and sieving. Among them, the technical threshold

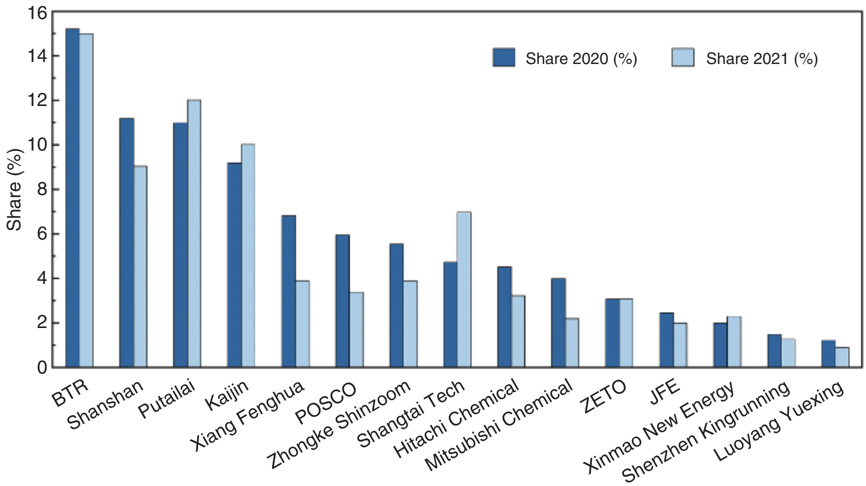

Figure 1.5 Market share of global anode material manufacturers in 2020–2021. *Source:* White Paper on global lithium-ion battery industry, Starting Point Research.

and production level of the negative electrode industry are mainly reflected in the two links of granulation and graphitization. Granulation needs to control the particle size, particle size distribution, and morphology of graphite, and these physical parameters directly affect the performance indicators of the anode material. For example, the smaller the particles, the better are the rate performance and cycle life, but the worse are the first-time efficiency and compaction density; therefore, a reasonable particle size distribution is required.

From a global perspective, companies from Japan and China have always dominated the market of anode materials (Figure 1.5). The top five Chinese companies, including Berterry (BTR), Shanshan, Putailai (Jiangxi Zichen), Kaijin, and Xiang Fenghua, account for more than half of the global market. According to the data from EVTank, due to the significant increase in demand for LIBs in various fields around the world, global shipments of anode materials reached 905 000 tons in 2021 with a year-on-year increase of 68.2%. From the perspective of negative electrode product structure, the proportion of artificial graphite products will further increase (Figure 1.6). Other anode materials represented by silicon-based anodes failed to achieve the expected growth due to the switch of the main shipment models of Chinese cylindrical battery products and the delay in the upgrade of the high-nickel system of square power LIBs, and their market share declined dramatically.

1.2.2.2 Lithium Titanate

The chemical formula of lithium titanate is $Li_4Ti_5O_{12}$, referred to as LTO, which has been studied by many energy workers because of its “zero strain” advantage. “Zero strain” means that the volume and lattice constant of the lithium titanate material change very little during the phase change. Therefore, the main advantages of lithium titanate are good cycle performance. The cycle life of lithium titanate energy storage batteries is more than 15 000 times, with the good charging rate in the range

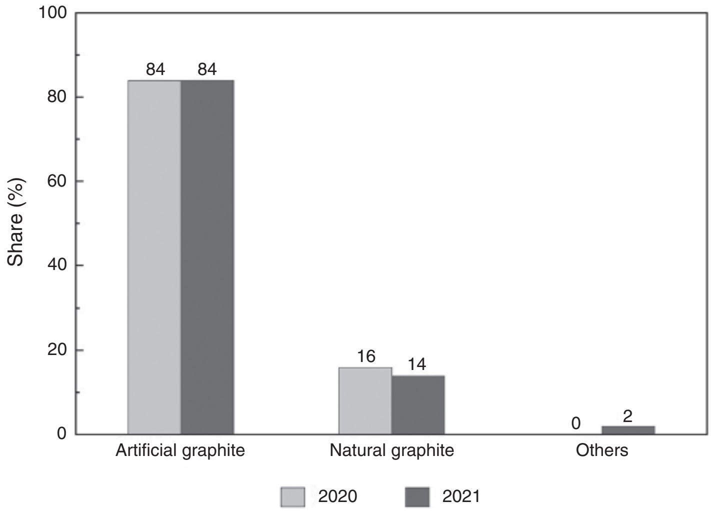

Figure 1.6 In 2020-2021, anode material industry structure. *Source:* GGII.

of 10–20 C. Lithium titanate also has a good low-temperature performance and still has 70% capacity in the extremely cold environment of −50 °C. Lithium titanate material has a low energy density, and its theoretical capacity is 175 mAh/g. At present, commercial lithium titanate has been developed to 170 mAh/g, and the first effect can be as high as 99.5%.

The industrial production method of lithium titanate still adopts the high-temperature solid-phase method. Usually, battery-grade TiO_2 and lithium salt $LiOH·H_2O$ or Li_2CO_3 are dispersed in water or organic solvent according to a specific stoichiometric ratio and mixed uniformly. After high-energy ball milling to nano-scale, spray-drying granulation, and high-temperature calcination, the final product lithium titanate is obtained.

In terms of industrialization, the leading companies include the American Ao Titanium Nano Technology Company (now acquired by Yinlong New Energy), Japan's Ishihara Industry Co., Ltd., and the British Johnson Matthey Corporation. There are Sichuan Xingneng New Material Co., Ltd. and Huzhou Weihong Power Co., Ltd. in China. Dong Mingzhu's perseverance to "Yinlong Titanium" made Yinlong's lithium titanate battery famous within a short period. With its fast-charging, low-temperature properties and safety characteristics, lithium titanate is widely used in public transportation buses and logistics vehicles that do not require high mileage. The market size of lithium titanate batteries is worth the wait.

1.2.2.3 Silicon Carbon

Silicon is the anode material with the highest theoretical capacity found so far. The theoretical specific capacity is 4200 mAh/g, which is 10 times more than that of graphite. Mixing silicon and graphite to form a silicon–carbon-based composite anode material not only combines the characteristics of good carbon conductivity and high silicon specific capacity but also can effectively buffer the expansion of silicon, which can significantly improve the overall electrochemical cycle performance of the material. From the commercialization path, the silicon–carbon material can be divided into silicon–carbon anode and oxygen–silicon–carbon anode materials.

The silicon–carbon anode material is first prepared by forming a precursor of nano-silicon and the matrix-graphite material through a granulation process, and the precursor is then prepared by surface treatment, sintering, pulverization, screening, demagnetization, and other processes. At present, the commercial application capacity of the silicon–carbon anode is about 450 mAh/g.

The silicon–oxygen negative electrode material is made by synthesizing pure silicon and silicon dioxide into silicon monoxide to form a silicon–oxygen negative electrode material precursor, and the precursor is then prepared into a modified SiO_x/C through the processes of pulverization, classification, surface treatment, sintering, sieving, demagnetization, etc. The modified SiO_x/C is then mixed with graphite according to the required capacity of the negative electrode, and a new type of oxygen–silicon graphite negative electrode material can be obtained; the capacities of the new oxygen–silicon graphite anode materials are mainly concentrated in two types: 420 and 450 mAh/g, with a small amount of 500 and 600 mAh/g. According to the China Powder Network, BTR's silicon-based anode products are at the leading position in the industry. It has made new breakthroughs in the development of silicon–carbon anode materials, and its specific capacity has been increased to 1500 mAh/g; BTR has completed a variety of technical development and mass production of sub-silicon products, and the specific capacity of some products reaches more than 1600 mAh/g. Snow's SiO product has a gram capacity of more than 500 mAh/g and the first coulombic efficiency is more than 89%, and it can achieve an 800-week cycle retention rate of more than 80%. It has completed the small-scale development and is in the stage of preparing for the pilot and mass production.

The industrialization of silicon-based anode batteries by global battery manufacturers is steadily advancing. As early as 2012, Japan's Panasonic has applied silicon carbon anodes to lithium batteries, while Hitachi Chemical is the largest supplier of silicon–carbon materials in the world as well as Japan's Shin-Etsu, Wu Yu Chemical, and American Ampris, all of which have deployed silicon carbon anode materials. The industrial application of silicon carbon anodes in our country is still at the initial stage. At present, CATL, BYD, GOTION, BAK, and Tianjin Lishen are all making efforts in the field of silicon–carbon materials, and BTR has achieved mass production. The high-tech lithium power grid predicts that the market demand for silicon-based anodes will exceed 30 000 tons in 2022, and the market size is expected to exceed 3.5 billion in the future.

1.2.3 Electrolyte

The electrolyte plays a role in transferring charge between the cathode and anode electrodes. According to the physical form of the electrolyte, it can be divided into liquid electrolyte, solid electrolyte, and solid–liquid composite electrolyte. Batteries that use solid electrolytes are called solid-state batteries.

1.2.3.1 Liquid Electrolyte

The function of the electrolyte is to transfer lithium ions between the anode and the cathodes, and the electrons are not transferred, which ensures the smooth progress of charging and discharging. Electrolyte is very important to the performance of lithium batteries and is known as the “blood” of LIBs. According to statistics from the Huajing Industrial Research Institute, electrolytes generally account for about 7–12% of battery costs. The general composition is a solvent, lithium salt, and additives. The most frequently used lithium salt is lithium hexafluorophosphate. The solvents are mainly carbonates, ethers, and carboxylates. According to their functions, additives can be divided into film additives, conductive additives, and flame retardant additives.

The preparation of the electrolyte is mainly divided into three sections: solvent synthesis, material mixing, and post-processing. Among them, the technical barrier is the composition of the formula at the material mixing stage. The electrolyte composition of different battery types is slightly different. The formula is basically dominated by downstream lithium battery companies, while the electrolytes of some subdivided into high-end consumer products or high-nickel power products are generally jointly developed by lithium battery companies and electrolyte companies. As the core key material of the electrolyte, lithium hexafluorophosphate is very deliquescent and needs to be synthesized in nonaqueous solvents such as anhydrous hydrogen fluoride and low alkyl ether, and the production conditions are extremely harsh.

Before 2010, the production capacity of lithium hexafluorophosphate was mainly concentrated in Japanese companies such as Stella, Kanto Denka, and Morita Chemical and the South Korean company Hosei. In 2011, Chinese companies’ hexafluoro carbon production capacity accounted for less than 15%. After 2011, companies such as Tianci High-tech (TINCI), Xinzhoubang, and other companies have achieved technological breakthroughs and began to expand their production significantly. In 2021, the market share of Chinese enterprises increased to more than 80% (Figure 1.7). According to the “White Paper on the Development of China’s Lithium-ion Battery Electrolyte Industry (2022)” released by EVTank, China’s electrolyte market will ship 507000 tons in 2021 with a year-on-year increase of 88.5%. According to the forecast of Guohai Securities, the global demand for lithium batteries will reach about 1200 GWh by 2025, corresponding to an electrolyte demand of about 1.32 million tons, with a compound annual growth rate of 35% during this period. The electrolyte market has a huge space.

1.2.3.2 Solid Electrolyte

Liquid electrolyte has hidden dangers such as volatile organic solvents and high-temperature flammability, and its development in the field of lithium batteries is very limited. The solid electrolyte is not only difficult to decompose at high temperatures, but it can also inhibit the generation of lithium dendrites, effectively alleviating the safety and durability of lithium batteries. Solid-state electrolyte is the core component

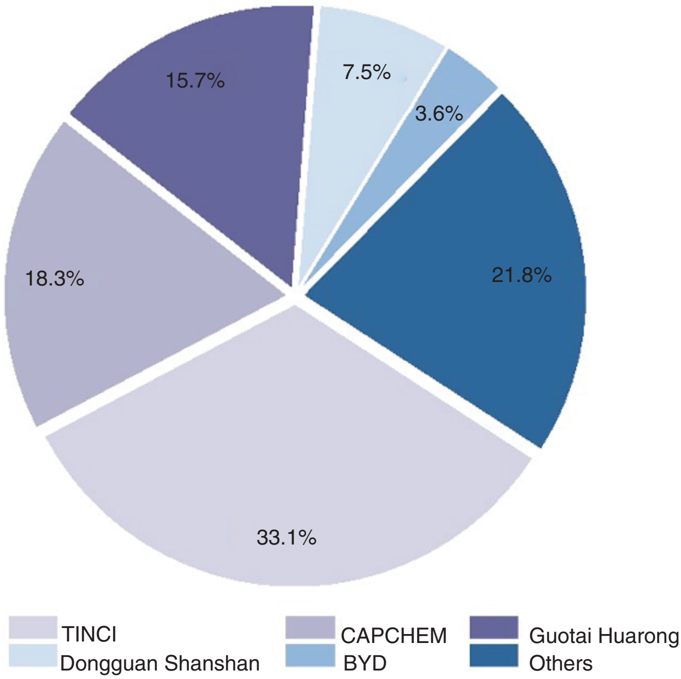

Figure 1.7 Market share of electrolyte in China in 2021. *Source*: Xinzhu Information, Huajing Industry Research Institute.

of solid-state lithium batteries and the technical focus of solid-state battery development. At present, solid electrolytes are mainly divided into three categories: polymer solid electrolytes, oxide solid electrolytes, and sulfide solid electrolytes.

The polymer solid electrolyte is complexed by a polymer matrix and a lithium salt. Commonly used lithium salts include $LiPF_6$, $LiClO_4$, and $LiAsF_4$. The matrix includes polypropylene oxide (PPO), polyvinylidene chloride (PVDC), polyethylene oxide (PEO), polyacrylonitrile (PAN), and polyvinylidene fluoride (PVDF). Representative types of oxide electrolytes include lithium lanthanum zirconium oxide (LLZO), lithium aluminum germanium phosphate (LAGP), and lithium aluminum titanium phosphate (LATP). The general process is to mix the desired oxidizing material with lithium source ball milling, press into tablets, and then calcine to increase the density. The sulfide solid electrolyte evolved on the basis of the oxide electrolyte, but the sulfide is really easy to react with water that generates the toxic H_2S gas. The production conditions are also harsh. At present, methods such as halide doping or introduction of new elements are used to improve its chemical stability in water (Table 1.2).

From the perspective of technology route of enterprise, Japanese and Korean enterprises mostly adopt sulfide solid electrolyte technology [10], Chinese enterprises mostly use oxide electrolytes, while European and American enterprises choose polymer, oxide, and sulfide routes. Solid electrolytes still have problems such

Table 1.2 Comparison of three solid electrolytes.

Classification	Subdivision	Representative enterprise	Advantages	Shortcomings
Organic electrolyte	Polymer	Bolloré, Solid Energy	Low-density, good viscoelasticity, and the most mature technology, taking the lead in small-scale mass production	Room temperature ionic conductivity is low Low theoretical energy density upper limit
Inorganic electrolyte	Oxide	Sakti3, ProLogium, QingTao Development, Beijing WeLion, Ganfeng Lithium Group	Excellent battery rate and cycle performance, commercial products are already available	Mechanically hard, the solid–solid interface is not in good contact, and the mass production cost is high
	Sulfide	Toyota, Samsung, Panasonic, CALT	The highest ionic conductivity, most likely to be used in batteries on a large scale	Unstable, high requirements on the production environment, difficult to develop

Source: Adapted from Evergrande Research Institute and Zhongqi Consulting.

as low interface stability, large-scale grain boundaries, vacancies, and local electronic conductance. Solid-state batteries have not yet formed an industrial chain. The "New Energy Automobile Industry Development Plan (2021–2035)" puts forward the requirements for strengthening the R&D and industrialization of solid-state batteries. For the first time, solid-state batteries have been raised to the national level, and solid electrolytes and solid-state batteries are expected to improve dramatically. According to industry chain research, solid-state batteries will be gradually commercialized in 2025 and become the main technical route for power batteries in 2030. According to Bank of China International Securities, the global demand for solid-state lithium batteries is expected to reach 494.9 GWh by 2030, with a market space of more than 150 billion yuan.

1.2.4 Separator

Separator is a key material to ensure the safety of battery system and affect its performance. It is placed between the cathode and anode as a device to isolate the electrodes. Therefore, the separator must have good insulation to prevent short circuiting of the cathode and anode electrodes or short circuits caused by burrs, particles, and dendrites. In addition, separator is a microporous channel with charging and discharging functions and rate performance. Therefore, the separator needs to have a certain tensile strength, puncture strength, high porosity, and uniform distribution.

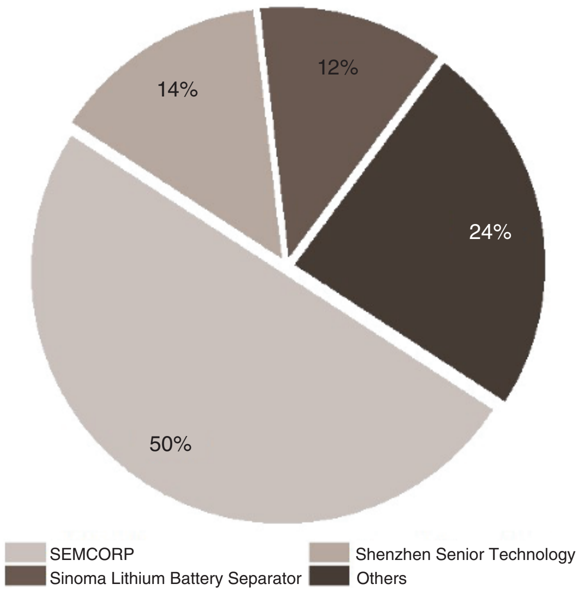

Figure 1.8 Pattern of separator for wet process in 2021. *Source:* Intelligence Research Group.

The pore size of separator is generally 0.03–0.05 or 0.09–0.12 μm; the thickness is generally less than 25 μm. By ensuring the mechanical strength, the thinner the separator, the better is the performance of the battery. The current mainstream wet base film products in the power market are mainly concentrated in the 9 and 12 μm fields. The 5 μm separator is mainly used in the field of consumer batteries. The mainstream materials for the separator are polypropylene (PP) microporous film and polyethylene (PE) microporous film. Separator is the material with the highest technical barrier among lithium battery materials. Microporous preparation technology is the core of the separator preparation process. Therefore, the separator process can be divided into dry and wet methods. The raw material of the dry process is generally PP; the process is simple, and the cost is low. The raw material of the wet process is generally PE, which has more advantages in high-power batteries and has relatively higher strength.

In recent years, the output and performance of Chinese wet process separator manufacturers have come closer to those of foreign companies; the production of separator has basically achieved localization, and their market share has continued to rise (Figure 1.8). However, there are still gaps in indicators, production technology, and equipment technology when compared with Japanese and American companies such as Asahi Kasei and Tonen. The separator company W-Scope estimates that the global lithium battery market will have 20 billion square meters of separator demand by 2025 and close to 32 billion square meters by 2030, which is 5.3 times that of 2020.

1.2.5 Binder

Binders are indispensable in LIBs, and their amount is very small, accounting for about 1–10% of the active material components. The main function of the binder is to bind the various components of the pole piece (active material and conductive agent) and the current collector together to form a stable pole piece structure, relieve the volume change of the electrode material during the charging and discharging process, and regulate dispersion effect of the slurry. Therefore, the binder must be able to withstand the swelling and corrosion of the electrolyte and the electrochemical effects of the charge and discharge process.

The current commercial binders include oil-based binder systems: mainly PVDF and PAN; aqueous binder system: sodium carboxymethyl cellulose (CMC), styrene butadiene rubber (SBR), sodium alginate (ALG), polyacrylic acid (PAA), and polyvinyl alcohol (PVA). At present, the cathode electrode of the battery is mainly PVDF binder, and *N*-methylpyrrolidone (NMP) is used as the solvent, accounting for up to 90%. The negative electrode material usually uses SBR as the binder, CMC as the thickener, and water as the solvent.

Solvay Group in Belgium, Kureha Co., Ltd. in Japan, Arkema Group in France, and Shanghai Sanaifu New Materials, Shandong Huaxia Shenzhou New Materials, Sinochem Lantian, etc., in China share the global lithium battery cathode binder PVDF market. Japan's Zeon Co., Ltd., Japan Paper, and China's Blue Ocean Blackstone Technology occupy the field of water-based adhesives. According to the statistical data, the output of lithium battery binders in China has increased annually in the past five years. As of 2021, it has reached 48 000 tons with a yearly increase of 34.5%. Benefiting from the rising demand for lithium batteries, China's lithium battery binders will also maintain rapid growth in the next five years. It is estimated that by 2025, China's lithium battery binder market is expected to approach 10 billion yuan.

1.2.6 Current Collector

The current collector is a component that is bonded to the outside of the cathode and anode electrodes in the battery and collects the current generated by the active material of the battery. It is one of the indispensable components in LIBs. Materials that can be used as current collectors for lithium batteries are metal conductor materials such as aluminum, copper, nickel, and stainless steel. With the continuous development of lithium battery technology, the trend of current collectors is to reduce the thickness and weight by ensuring new energy.

1.2.6.1 Copper Foil

Copper has many advantages such as excellent electrical conductivity, good ductility, and abundant resources. It is easily oxidized at a higher potential and is often used as a current collector for negative electrode active materials such as graphite, silicon, tin, and cobalt–tin alloy. The quality and cost of a copper foil account for about 13% and 8% of the total mass and total cost of a typical lithium battery, respectively [11]. There are mainly two types of copper foil: rolled and electrolytic ones. Rolled copper foil is an original foil made by repeatedly rolling a copper plate several times, and roughening treatment is carried out according to the requirements. Electrolytic copper foil is made by electrodepositing copper solution in a special dissolving vessel under the action of direct current with copper sulfate electrolyte and then undergoing a series of surface treatments to obtain copper foil with smooth and rough surfaces. When copper foil is used as a current collector, the thickness is reduced from 12 to 10 μm and then to 8 μm. Up to now, most battery manufacturers use 6 μm for mass production.

According to the statistics of the Huajing Industry Research Institute, the global lithium battery copper foil production capacity will be a total of 435 000 tons in 2020. China and South Korea are the main lithium battery copper foil production countries; the top three companies in terms of production capacity are Nordisk, Lingbao Huaxin, and Jiujiang De Blessing. Affected by the increase in demand for upstream power batteries, copper foil companies of lithium battery have actively expanded their production. According to Gaogong Lithium battery, the global demand of copper foil for lithium batteries in 2021 is 380 000 tons with a yearly increase of 52%, of which the demand for power batteries is 240 000 tons (an annual increase of 75%); the total global demand of copper foil for lithium batteries is expected to be 10 000 tons in 2025, and the demand of copper foil for lithium battery will expand three times in the next five years.

1.2.6.2 Aluminum Foil

Aluminum foil is currently the main cathode current collector for LIBs. It has the advantage of good conductivity, light weight, and low cost, and the passivation layer on its surface can avoid electrolyte corrosion during the charging and discharging process. According to the composition and impurities, aluminum foil can be divided into 1 series, 3 series, and 8 series, corresponding to pure aluminum, aluminum manganese series, and other aluminum alloy series, respectively. Aluminum foil has been reduced from 16 to 14 μm and then to 12 μm in past years. Presently, many battery manufacturers have mass-produced aluminum foil of 10 μm and even 8 μm. The production of aluminum foil is to roll the aluminum foil blanks to the required thickness through multiple rolling and heat treatments. After two processes of rough rolling and finishing rolling, the aluminum foil is surface-treated, and finally, the aluminum foil is slit into the width and length required by the lithium battery manufacturer. Recently, more studies have been done on carbon-coated aluminum foil, where a thin layer of conductive carbon is coated on the surface of a normal aluminum foil to optimize the performance of battery.

Aluminum foil of lithium batteries can be divided into power battery foil, consumer battery foil, and energy storage battery foil. Among them, power battery foil is currently in the largest demand, accounting for more than 50%. Foreign suppliers of aluminum foil for lithium batteries are mainly concentrated in Japan, such as Toyo Aluminum and Hitachi Metals. Domestically, there are Dingsheng New Materials, Wanshun New Materials, Huaxi Aluminum, Nannan Aluminum, Sifangda, etc. Benefiting from the high growth in demand for power batteries and energy storage batteries, leading lithium batteries have expanded their production. According to Huaan Securities, based on the consumption of 400–600 tons of aluminum foil per GWh lithium battery, it is estimated that the global lithium battery aluminum foil is expected to reach 454–681 000 tons in 2025. The Na-ion press conference of CATL is expected to realize the industrial chain in 2023. The anode and cathode of sodium-ion batteries are made of aluminum foil. By then, the market space of lithium-ion aluminum foil will expand.

1.2.6.3 Others

Nickel is relatively inexpensive, has a good electrical conductivity, and is relatively stable in acid and alkaline solutions. Nickel can be used as both a cathode electrode current collector and a negative electrode current collector. Nickel is matched with both cathode active material LFP and negative active materials such as nickel oxide, sulfur, and carbon–silicon composite materials. The shape of the nickel current collector usually has two types: foamed nickel and nickel foil. Due to the well-developed pores of the foamed nickel, the contact area with the active material is large, thereby reducing the contact resistance between the active material and the current collector. However, when nickel foil is used as an electrode current collector, as the number of charging/discharging process increases, the active material is likely to fall off, which greatly affects the performance of the battery.

Stainless steel refers to alloy steel containing nickel, molybdenum, titanium, silver, copper, iron, and other elements, which also has good electrical conductivity. It is stable enough to resistant to corrosive media such as air, steam, water, acid, alkali, and salt. The surface of stainless steel is also easy to form a passive film, which can protect its surface from corrosion. At the same time, stainless steel can be processed thinner than copper, which has the advantages of low cost, simple process, and large-scale production.

Carbon nanotubes (CNTs) are a new type of one-dimensional nanomaterials. The unique graphitized structure and ultra-high aspect ratio of CNTs result in its excellent electrical properties; at the same time, the density of CNTs is extremely low compared to that of metals. Therefore, the thin film prepared with CNTs is expected to replace aluminum and copper foil and become a new-generation LIB collector.

1.3 Development and Trends in Power Lithium-Ion Battery

1.3.1 The Layout of Lithium-Ion Battery Production Capacity

In 2025, the global power battery demand will exceed 1 TWh. Driven by the high demand, power battery companies are vigorously expanding their production capacity. According to incomplete statistics of the starting point lithium battery, as of August 2021, 20 Asian companies including CATL, LG New Energy, CALB, Yiwei Lithium, SKI, and BYD, have a planned production capacity of more than 3000 GWh. In the past two years, European and American companies are accelerating the deployment of power LIBs. A report published in June by EU NGO Transport and Environment (T&E) put the total number of Gigafactory's built or under construction in existing projects in Europe to 38, with a combined expected annual output of

1000 GWh. Across Europe, several local battery companies, including Sweden's Northvolt, France's Verkor, Britain's Britishvolt, Norway's Freyr, and Slovakia's InoBat Auto have been established, and large-scale battery production plans have been announced. In addition, Germany plans to invest 1 billion euros to support German lithium-ion power battery production by 2021. With the successive completion of 38 super factories, the production of electric vehicle batteries in Europe will also increase significantly. It is expected to produce 460 GWh in 2025 and 1140 GWh in 2030, which is 13 times of the expected supply this year (87 GWh). In addition, to ensure the supply of batteries, major car companies have begun to build their own lithium-ion power battery factories to achieve cost control and control the initiative of lithium-ion power battery supply. Among them, Tesla plans to build the future Gigafactory near Berlin into one of the largest factories in the world, with an expected production capacity of 250 GWh in 2030. Volkswagen Group plans to join hands with its partners to build six battery factories in Europe. Overall, Europe is expected to become the world's second largest supplier of power LIBs for electric vehicles in the near future, which will bring huge challenges to the Asian lithium-ion power battery market.

1.3.2 The Changing Trend of Lithium-Ion Battery Material Types

Statistics from SMM show that the total installed capacity of power LIBs in China continues to grow from 16 GWh in 2015 to 154 GWh in 2021 (Figure 1.9). In terms of battery types, NCM batteries and LFP batteries dominate the lithium-ion power

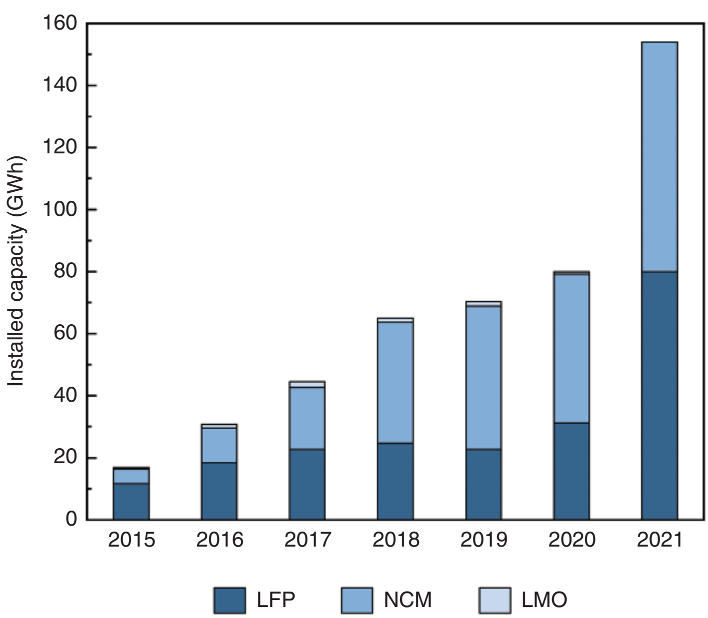

Figure 1.9 Main power batteries by material types and their installed capacities in China from 2015 to 2021. *Source:* SMM.

battery market. The high energy density of NCM batteries is gradually favored by the passenger vehicle market, reaching more than 60% in 2019. LFP batteries are mainly used in commercial vehicles and pure electric passenger vehicles. With the introduction of BYD's blade battery technology in 2020 and the advancement of battery assembly technology, low-cost LFP batteries will achieve breakthroughs in energy density. It will lead to an increase in the sales of LFP batteries in the short term; thus, the market share will rebound in 2020–2021.

1.3.3 Development Goals and Plans in Various Regions of the World

Since the commercial use of LIBs in 1991, the battery system with the LCO/LMO/LFP as the cathode electrode and the graphite as the anode electrode has basically been inherited. In recent years, due to requirements for the higher energy and safety of power LIBs, its technological development was thus boosted. Figure 1.10 shows the development history, status, and future trends of lithium batteries around the world [12]. It is worth noting that the energy density of the Panasonic 18650 battery has only approximately tripled between 1990 and 2015. At present, lithium batteries with an energy density of 240 Wh/kg have achieved mass production, and lithium batteries with an energy density of 300 Wh/kg or even 400 Wh/kg are still in development. As a result, countries worldwide are developing and planning to achieve electric vehicle range (>500 km, charging time <20 minutes) and cycle life (>3000 cycles).

In China, the power battery development plan at various stages is very clear. The "Technical Roadmap for Energy-Saving and New Energy Vehicles" has detailed the corresponding requirements for each stage of China's power LIBs and new type batteries, which are mainly divided into three stages:

(1) In 2020, LIBs should meet the needs of pure electric vehicles over 300 km, that is, the energy density of a single unit will reach 300 Wh/kg and 600 Wh/L,

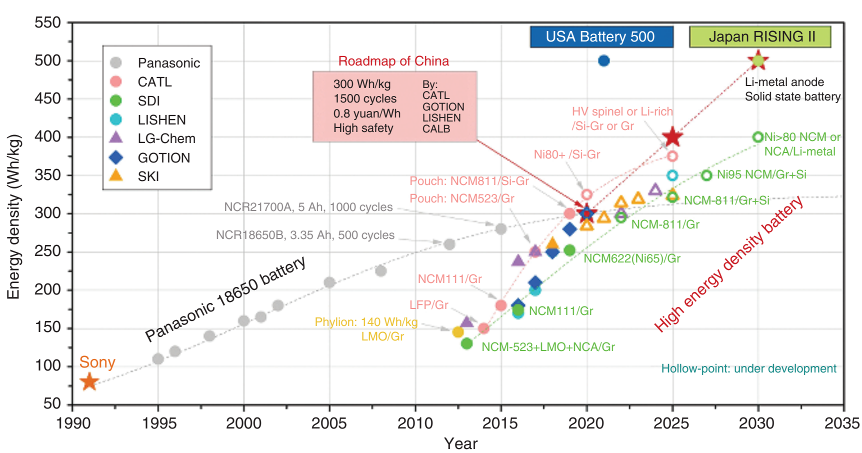

Figure 1.10 The history, current state, and development route of LIBs.
Source: Lu et al. [12] / with permission of Elsevier.

the unit cost will be reduced to 0.8 yuan/Wh, and the cycle life will be 1500 times;

(2) In 2025, LIBs should meet the needs of pure electric vehicles over 400 km, that is, the energy density of a single unit will reach 400 Wh/kg and 800 Wh/L, the unit cost will be reduced to 0.5 yuan/Wh, and the cycle life will be 2000 times;

(3) In 2030, LIBs should meet the needs of pure electric vehicles over 500 km, that is, the energy density of a single unit will reach 500 Wh/kg and 1000 Wh/L, the unit cost will be reduced to 0.4 yuan/Wh, and the cycle life will be 3000 times.

At present, against the goal of 300 Wh/kg, the research on power LIB technology mainly focuses on the development of Li-rich ternary cathode materials, silicon–carbon anodes, and electrolytes with wide voltage windows.

For example, Li-rich layered oxides (LLOs) deliver extraordinary capacity exceeding 250 mAh/g have greatly attracted research interests to further contribute the energy density. Despite the high capacity, LLOs suffer from poor rate performance and voltage fading as well as capacity decay during cycling. Guo et al. [13] from the Ningbo Institute of Materials Technology and Engineering (NIMTE)-CAS constructed abundant nanoscale defects via chemical delithiation and built dual Al2O3 layer via hierarchical surface configuration to suppress surface lattice oxygen release. Besides, they also designed 3D porous LLO and created oxygen vacancies through gas-solid interface reaction, facilitating the ionic diffusion to enable excellent rate capability [14]. Based on the scientific achievements, a 300-ton pilot production line of LLO cathode material has been established. By 2030, all-solid-state (ASS) batteries are expected to achieve large-scale commercialization, which will further promote the application of metallic lithium anodes to meet the energy density requirement of 500 Wh/kg.

In Japan, New Energy and Industrial Technology Development Organization (NEDO) released "Research and Development Initiative for Scientific Innovation of New Generation Battery" (RISING II) project in 2018. In terms of power batteries, they also focus on the research and development of ASS batteries. By 2025, the first generation of ASS batteries will be popularized, and its energy density will reach 300 Wh/kg. By 2030, the second generation will be popularized and is expected to realize 500 Wh/kg. In addition, Japan is also striving for developing new types of batteries such as sulfide-based ASS batteries and zinc-based batteries.

In South Korea, the Korea Battery Industry Association set the power electricity roadmap and four key materials roadmaps in 2018. The specific energy density of power battery will reach 330 Wh/kg and 800 Wh/l in 2025, and the cycle life of power battery will reach 15 years with 1000 cycles.

Europe: LIBs are part of the EU's efforts to develop a decarbonized and renewable energy society. The "Horizon 2020" plan, the latest framework of the EU's 10-year economic development plan, proposes to invest a total of 77.028 billion euros in industry, scientific research, business, and other fields from 2014 to 2020, of which a total of 114 million euros are earmarked for batteries, including lithium battery materials and transmission models and research and innovation of advanced lithium batteries. The energy density of power LIBs will reach 250 Wh/kg in 2025 and will continue to increase to 500 Wh/kg by 2030. In addition, the energy technology strategic development plan "Battery 2030+" proposes to invest more than 100 billion euros to promote the comprehensive development of the lithium-ion power battery industry chain, covering the entire process from raw materials to battery recycling.

The United States: The US Department of Energy (DOE) established the Battery 500 program in 2021. The total investment in the next five years is more than US$ 50 million, and the goal is to develop lithium metal batteries and replace the existing graphite anode with metal lithium, so that the energy density can reach 500 Wh/kg and the number of cycles will be 1000 times.

1.3.4 Critical Challenges for the Future Lithium-Ion Power Battery Industry

1.3.4.1 Reducing the Cost of Lithium-Ion Power Battery

The cost of raw materials accounts for more than 60%, which is the key way to reduce the overall cost of power battery [14]. Among them, the cost reduction of cathode materials lies in the metal resource price of upstream Li, Co, and Ni and the manufacturing process; the cost reduction of anode material lies in the raw material purchase of needle coke and graphite processing technology; the cost reduction of separator material lies in the improvement of the yield of the production process and the improvement of equipment; and the cost reduction of electrolyte is limited, and its large-scale production may help to reduce the price. However, under the existing technology, the cost reduction space for raw materials is very limited. The focus of cost reduction will be at the module and pack level, such as BYD's introduction of blade technology, which will reduce battery system costs by 20–30%.

1.3.4.2 Improving the Energy Density of Power Battery

The path of energy density improvement mainly includes two aspects: core density and system density. In terms of cells, new technological breakthroughs such as ASS and ternary Li-rich batteries need to be achieved, and technologies such as changing the ratio of cathode and anode electrodes electrode materials need to be optimized. In terms of battery packs, the modular cell-to-pack (CTP) scheme is designed to improve the efficiency of battery pack grouping, optimize the layout structure, and use low-density materials. For example, CATL's CTP technology, based on a NCM material battery technology architecture, can increase space volume utilization by 15–20%, reduce the number of internal components by 40% and indirectly increase system energy density by 10–15%. In addition, the blade battery designed by BYD based on LFP battery technology architecture can increase the volume energy density by 50%.

1.3.4.3 Improving Safety of Power Battery

Fire concerns of power battery generally includes charging spontaneous combustion (charging current is large), collision combustion (battery damage, internal short circuit), driving spontaneous combustion (battery damage, internal short circuit), and wading spontaneous combustion (battery sealing is insufficient, liquid causes external short circuit). These problems can cause the whole battery pack temperature to rise sharply, thermal runaway, and then spontaneous combustion explosion. Battery thermal runaway can be controlled by battery design or supporting facilities. For example, it can prevent the cathode electrode from releasing oxygen; suppressing the flammability of electrolyte; improving the sealing, heat insulation, and impact resistance of battery pack structure; and optimizing the battery thermal runaway management system.

1.3.4.4 Recycling Power Battery

The full life cycle of power battery involves many subjects and links. Only some enterprises master the life cycle data of their products, and the fragmentation of information restricts the recycling and reuse of power LIBs. In addition, retired batteries lack testing standards, and battery residual value assessment technology as well as the talent reserves are insufficient. In the process of battery design and manufacture, the manufacturers did not consider recycling and disposal factors.

1.4 Analysis of the Supply and Demand of Critical Metal Raw Material Resources for Power Lithium-Ion Batteries

LIBs play a crucial role in global electrification and help to tackle climate change. Global battery demand is expected to scale up 19 times compared to the current level by the end of 2030 [15]. This can be hardly achieved if relying on the current way of how the materials are sourced, produced, and used. The challenge can only be overcome with the collaborative efforts through the entire value chain. Among all the challenges, the supply of critical metal raw materials, i.e. lithium, nickel, and cobalt, are one of the most tough ones. Material production of lithium battery is very dependent on these critical metals. A recent report by the IEA suggests a typical electric car requires six times the mineral inputs of a conventional car [16], and currently, they are predominantly extracted from minerals on earth. These minerals are unevenly distributed geographically, with lithium raw material mainly produced in Australia, nickel in ASEAN countries (Indonesia and Philippines), and cobalt in the Democratic Republic of Congo (DRC). The scale-up in mineral sourcing might lead to negative social, environmental, and integrity impacts in these regions, especially for cobalt. The DRC is one of the world's least developed countries, whose economy hugely relies on cobalt. A total of 10–12 million people depend directly or indirectly on mining, and 80% of exports are mining products. However, severe social risks have been well documented in the DRC's artisanal mining industry, which include hazardous working conditions, deaths due to poorly secured tunnels, potentially various forms of forced labor, the worst forms of child labor, and exposure to fine dusts and particulates as well as the DNA-damaging toxicity [15]. All these issues have resulted in a rather fragile front-end LIB supply chain.

At the same time, driven by the strong demand in the field of lithium batteries, the price of these key metal materials has shown a rapid upward trend since the beginning of 2021, showing supply shortages of varying degrees.

To underscore the importance and potential risks associated with these critical metal resources, the White House's 100-day review under Executive Order 14017, issued in June 2021, dedicated an entire chapter to review the topic and concluded that reliable, secure, and resilient supplies of key strategic and critical materials are essential to the US economy and national defense.

In the successive part of this chapter, the geographical distribution of lithium, nickel, and cobalt and their production status have been introduced, followed by a discussion on the supply and demand outlook.

1.4.1 Geographical Distribution of Critical Metal Raw Materials and Their Production Status

1.4.1.1 Lithium

Lithium is a relatively rare element on earth, whose abundance in the earth's crust is 0.0065%, ranking 27th. Although seawater contains rich lithium resources, around 260 billion tons, currently it is not commercially available as the content is low, only 0.17 mg/l.

According to the latest USGS report [17], in 2020, the global lithium mine reserves were approximately 21.06 million tons. Among them, Chile has the most reserves, about 9.2 million tons, accounting for about 43.7% of global reservation. Australia ranks second in reserves, with reserves of about 4.7 million tons in 2020, accounting for 22.3% of global reserves. Argentina ranks the third in resource reserves. The detailed data of global lithium reserves in 2020 are listed in Table 1.3.

The global lithium resources are mainly divided into two types, namely rock minerals and brine minerals, of which closed basin brine accounts for 58%; pegmatite (including lithium-rich granite) accounts for 26%; hectorite clay accounts for 7%; and oilfield brine, geothermal brine, and lithium borosilicate ore each account for 3% [18].

The world's brine lithium resources are mainly distributed in the "Lithium Triangle" plateau areas of Chile, Argentina, and Bolivia in South America; western United States; and western China. The world's rock lithium resources are mainly distributed in Australia, China, Zimbabwe, Portugal, Brazil, Canada, Russia, and other countries.

Approximately 82 200 metric tons of lithium ore were mined in 2020 globally. Australia is the main contributor, with 40 000 metric tons lithium yield, accounting for almost half of the world's production, followed by Chile and China, with 21.9% and 17.0% contributions, respectively. The detailed data of global lithium mine yield in 2020 are listed in Table 1.4.

1.4.1.2 Nickel

According to the latest USGS report [17], in 2020, the global nickel mine reserves were approximately 94 million tons. Among them, Indonesia has the most reserves, about 21 million tons, accounting for about 22.4% of world total. Australia ranks

Table 1.3 Global lithium mine reserves in 2020.

Country	Lithium mine reserves (metric tons)	Percentage (%)
United States	750 000	3.6
Argentina	1 900 000	9.0
Australia	4 700 000	22.3
Brazil	95 000	0.5
Canada	530 000	2.5
Chile	9 200 000	43.7
China	1 500 000	7.1
Portugal	60 000	0.3
Zimbabwe	220 000	1.0
Rest of world	2 100 000	10.0
World total	21 055 000	100

Source: Data from USGS [17].

Table 1.4 Global lithium mine yield in 2020.

Country	Lithium mine yield (metric tons)	Percentage (%)
United States	—	—
Argentina	6 200	7.5
Australia	40 000	48.7
Brazil	1 900	2.3
Canada	—	—
Chile	18 000	21.9
China	14 000	17.0
Portugal	900	1.1
Zimbabwe	1 200	1.5
Rest of world	—	—
World total	82 200	100

Source: Data from USGS [17].

second in reserves, with the amount of about 20 million tons in 2020, accounting for 21.3% of global reserves. Brazil ranks third in resource reserves. The detailed data of global nickel reserves in 2020 are listed in Table 1.5.

The global nickel resources are mainly divided into two types: laterite nickel and nickel sulfide ore, which account for 60% and 40% of total reserves, respectively. Laterite nickel mines are mainly distributed in countries within the Tropic of Cancer, including Australia, New Caledonia, Indonesia, Brazil, and Cuba, while

Table 1.5 Global nickel mine reserves in 2020.

Country	Nickel mine reserves (metric tons)	Percentage (%)
United States	100 000	0.1
Australia	20 000 000	21.3
Brazil	16 000 000	17.0
Canada	2 800 000	3.0
China	2 800 000	3.0
Cuba	5 500 000	5.9
Dominican Republic	—	—
Indonesia	21 000 000	22.4
New Caledonia	—	—
Philippines	4 800 000	5.1
Russia	6 900 000	7.3
Rest of World	14 000 000	14.9
World total	93 900 000	100

Source: Data from USGS [17].

nickel sulfide mines are mainly distributed in Russia, Canada, Australia, South Africa, and China.

Laterite nickel mines are mostly open-pit mines, which are convenient for mining, but the processing technology is more complicated due to their low grade. With the recovery of nickel prices and progress in the refining technology, the proportion of primary nickel produced from laterite ore has steadily increased. The proportion of nickel supply from laterite ore increased from 51% in 2017 to 62% in 2019, which has completely changed the previous dominated industry pattern of sulfide ore.

Approximately 2.5 million metric tons of nickel ore were mined globally in 2020. The main contribution comes from the ASEAN region, where Indonesia produced 0.76 million tons (accounting for 30.7% of world's production), and Philippines produced 0.32 million tons with 12.9% worldwide share. Russia ranks third, with a yield of 0.28 million tons similar to that of Philippines, accounting for 11.3% of the global total. The detailed data of global nickel mine yield in 2020 are listed in Table 1.6.

1.4.1.3 Cobalt

According to the latest USGS report [17], in 2020, the global cobalt mine reserves were approximately 7.1 million tons. Among them, Congo has the most reserves, about 3.6 million tons, accounting for about 50.5% of the world's total. Australia ranks second in reserves, with reserves of about 1.4 million tons in 2020, accounting for 19.6% of global reserves. Cuba ranks the third in resource reserves. The detailed data of global cobalt reserves in 2020 are listed in Table 1.7.

Table 1.6 Global nickel mine yield in 2020.

Country	Nickel mine yield (metric tons)	Percentage (%)
United States	16 000	0.6
Australia	170 000	6.9
Brazil	73 000	2.9
Canada	150 000	6.1
China	120 000	4.8
Cuba	49 000	2.0
Dominican Republic	47 000	1.9
Indonesia	760 000	30.7
New Caledonia	200 000	8.1
Philippines	320 000	12.9
Russia	280 000	11.3
Rest of World	290 000	11.7
World total	2 475 000	100

Source: Data from USGS [17].

Table 1.7 Global cobalt mine reserves in 2020.

Country	Cobalt mine reserves (metric tons)	Percentage (%)
United States	53 000	0.7
Australia	1 400 000	19.6
Canada	220 000	3.1
China	80 000	1.1
Congo	3 600 000	50.5
Cuba	500 000	7.0
Madagascar	100 000	1.4
Morocco	14 000	0.2
Papua New Guinea	51 000	0.7
Philippines	260 000	3.6
Russia	250 000	3.5
South Africa	40 000	0.6
Rest of World	560 000	7.9
World total	7 128 000	100

Source: Data from USGS [17].

Table 1.8 Global cobalt mine yield in 2020.

Country	Cobalt mine yield (metric tons)	Percentage (%)
United States	600	0.4
Australia	5 700	4.2
Canada	3 200	2.4
China	2 300	1.7
Congo	95 000	70.4
Cuba	3 600	2.7
Madagascar	700	0.5
Morocco	1 900	1.4
Papua New Guinea	2 800	2.1
Philippines	4 700	3.5
Russia	6 300	4.7
South Africa	1 800	1.3
Rest of World	6 400	4.7
World total	135 000	100

Source: Data from USGS [17].

Cobalt rarely forms separate ores and is mostly associated with copper, nickel, manganese, iron, arsenic, lead, and other deposits. Cobalt resources usually exist in the following areas [17]: sediment-hosted stratiform copper deposits in Congo and Zambia; nickel-bearing laterite deposits in Australia and its nearby island countries, i.e. Indonesia, Philippines, New Caledonia, and Cuba; magmatic nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States; manganese nodules and crusts on the floor of Atlantic, Indian, and Pacific Oceans

The total yield of cobalt mine was 135 000 metric tons in 2020, predominantly from Congo. Congo alone has produced 95 000 tons, contributing to over 70% of the global total. Russia and Australia ranked second and third, accounting for 4.7% and 4.2%, respectively. The detailed data of global nickel mine yield in 2020 are listed in Table 1.8. Compared to lithium (Table 1.4) and nickel (Table 1.6), cobalt presents the most unbalanced global supply, which is extremely dependent on a single country, i.e. Congo.

1.4.2 Supply and Demand Outlook of Critical Metal Raw Materials

1.4.2.1 Lithium

The Lithium Carbonate Equivalent (LCE) in 2020 is around 369 000 tons, among which, LIBs account for 59%, while the rest 41% comes from the industrial fields. The demand domain in LIB can be further divided into consumer electronics, electric vehicles, electric mobilities, e.g. scooters, electric bikes, and energy storage.

While electric vehicles have only begun to grow in the last few years, their share is increasing very fast, already consuming 35% of global lithium demand. Energy storage is another fast-growing area, benefiting from energy transition to solar and wind, although it contributed only 3% in 2020.

In the industrial field, lithium is normally used as a raw material for glass and ceramics, grease, flux, and polymers, and it can also be used in solid fuels, aluminum smelting, and other fields. Lithium demand in the industrial field is rather stable, and its share in total lithium demand will be significantly reduced with the massive adoption of electric vehicles and energy storage (Figure 1.11).

1.4.2.2 Nickel

The total nickel demand in 2020 is around 2.39 million tons [18]. As the main characteristics of nickel are high hardness and oxidation resistance, most of the world's finished nickel (near 70%) has been used in the production of stainless steel. The major applications for nickel and their corresponding demand share are illustrated in Figure 1.12.

The contribution from the battery sector only account for 6% of the overall nickel consumption in 2020, which is dramatically different from that of lithium (Figure 1.11) and cobalt (Figure 1.13), where the contribution from the battery sector is greater than 50%. However, with the continuous advancement of electric vehicles, the demand for nickel in the battery industry is expected to grow rapidly in the next few years. Nickel sulfate is a key raw material for LIBs, mainly used in the production of NCM and NCA battery precursors/cathode materials. The market

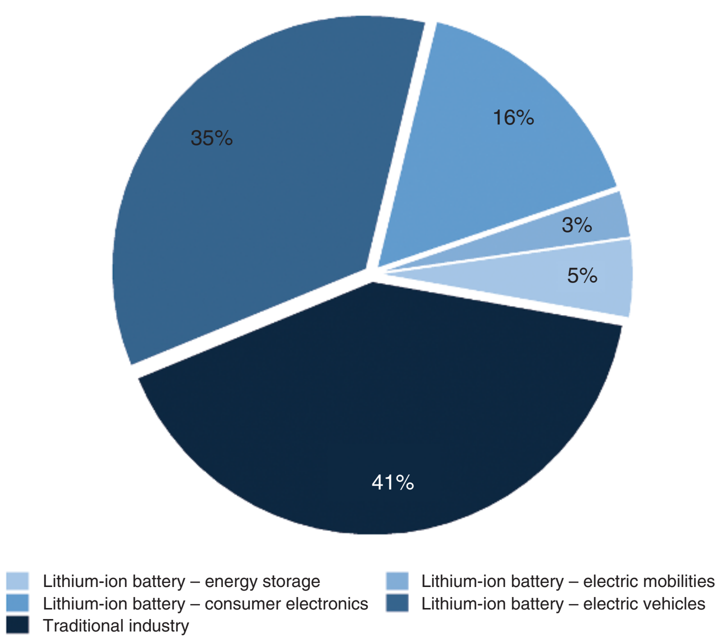

Figure 1.11 Lithium demand by application in 2020. *Source:* Data from Antaike [18].

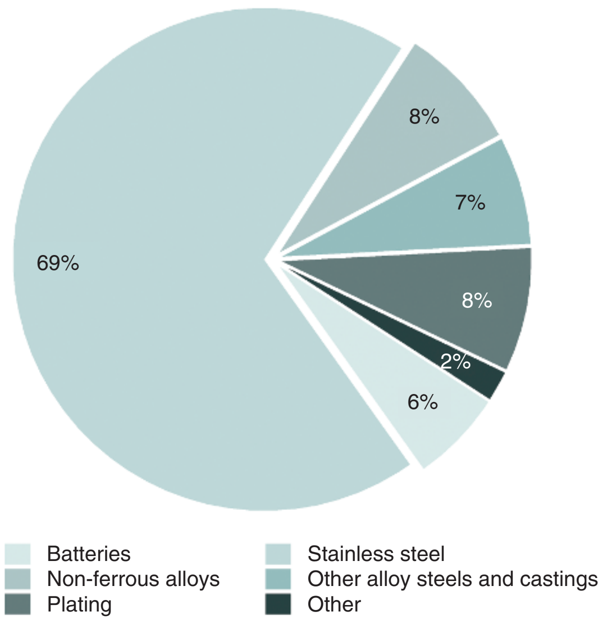

Figure 1.12 Nickel demand by application in 2020.
Source: Adapted from Fraser et al. [19].

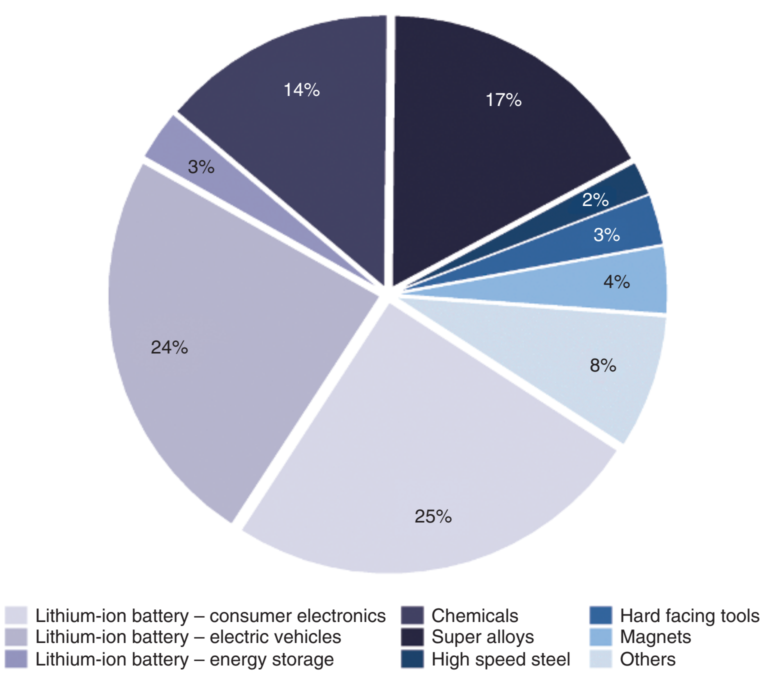

Figure 1.13 Cobalt demand by application in 2020. *Source*: Cobalt Institute [20].

presently is moving toward NCM ternary batteries of high nickel content because of the pursue for higher battery energy density and continued cost reduction (to replace cobalt with nickel to reduce total raw material cost), and the considerations of supply chain security, thereby further stimulating the demand for nickel in batteries.

1.4.2.3 Cobalt

The total cobalt demand in 2020 is around 140 000 tons [18], where metallurgical application accounts for 48% and LIBs for the rest 52%. The details can be found in Figure 1.13. For metallurgical application, cobalt's strength and resistance nature at high temperature make it an ideal choice to produce high-temperature alloys in power plants, high-speed steel drill bits, and blades as well as for use in hard face, carbide, and diamond tools for cutting applications and magnets. In addition, cobalt can also be used to make catalysts and desiccants. As for the LIB, cobalt is an important raw material for its manufacturing. Cobalt tetraoxide is used for LCO battery cathode, whereas cobalt sulfate is used for cathode material of ternary NCM and NCA battery. In the past 10 years, the growth in demand for cobalt has mainly come from the development of 3C batteries, such as use in smartphones, tablets, laptops, notebooks, computers, etc. Due to the rapid adoption of electric vehicles, the increase in cobalt demand is mainly driven by the battery sector in these two years, therefore, adding up the proportion of cobalt used in LIBs.

1.4.3 Scenario Without Recycling

Various research organizations [15, 21, 22] have predicted that due to energy transition toward renewable energy, especially in the electric vehicle and energy storage sectors, the demand for lithium, nickel, and cobalt will experience a huge increase in this decade and onward. Global battery alliance (GBA) [15, 21] predicts 6.4 times increase of lithium, 2.1 times increase of cobalt, and 24 times increase of class I nickel in 2030 as compared to that in 2018 [15]. The prediction from IEA is even more aggressive; according to their sustainable development scenario (SDS), the demand of lithium will grow by 43 times, nickel by 41 times, and cobalt by 21 times in 2040 when compared with that in 2020 [21].

At present, the supply of either lithium, nickel, or cobalt mainly comes from primary mineral resources. From the initial mine exploration to a new mine that can be officially put into operation is a long process, which usually takes up more than 10 years. Because of this, it is rather difficult to fulfill such tremendous growth; lithium, nickel, and cobalt minerals all have their key challenges [22], which are summarized below in Table 1.9, and all of them will experience shortage in this decade.

IEA predicts that the deficit in lithium supply will start from 2023 onward accompanied by a rapid gap increase, though the supply and demand unbalance may even begin in 2021. As for cobalt, the supply shortage will occur from 2024 and experience a similar trend as lithium. Nickel's supply is the most secure among the three, where the unbalance only starts from 2028 (Figure 1.14).

Table 1.9 Lithium, nickel, and cobalt minerals key challenges.

Mineral	Key challenges
Lithium	• Possible bottleneck in lithium chemical production as many smaller producers are financially constrained after years of depressed prices • Lithium chemical production is highly concentrated in a small number of regions, with China accounting for 60% of global production (over 80% for lithium hydroxide) • Mines in South America and Australia are exposed to high levels of climate and water stress
Nickel	• Possible tightening of battery-grade Class 1 supply, with high reliance on the success of HAPL projects in Indonesia; HAPL projects have track records of delays and cost overruns • Alternative Class 1 supply options (e.g. conversion of NPI to nickel matte) are either cost-prohibitive or emissions-intensive • Growing environmental concerns around higher CO_2 emissions and tailings disposal
Cobalt	• High reliance on the DRC for production and China for refining (both around 70%) set to persist, as only a few projects are under development outside these countries • Significance on artisanal small-scale mining makes the supply vulnerable to social pressures • New supply is subject to developments in nickel and copper markets as some 90% of cobalt is produced as a by-product of these minerals

Source: Data from IEA [22].

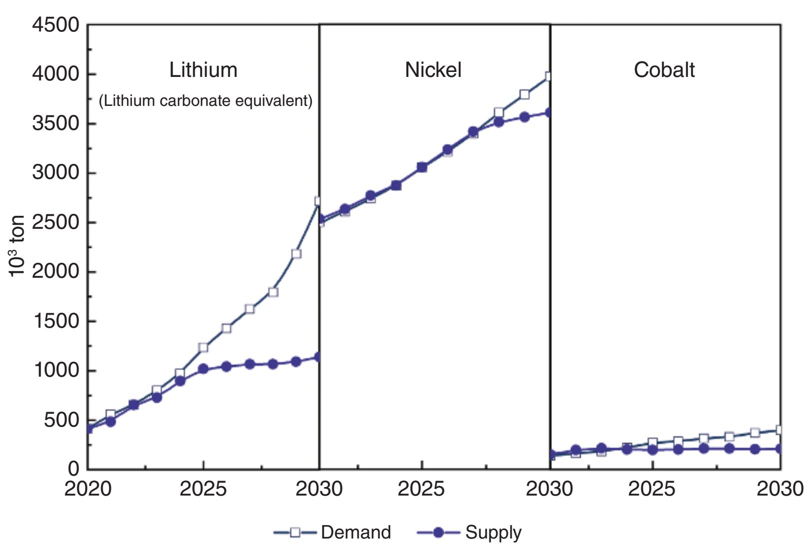

Figure 1.14 Supply and demand forecast for lithium, nickel, and cobalt.
Source: Data from IEA [22].

1.4.4 Scenario with Recycling

Metal recycling has the potential to be a significant resource of secondary supply, although it comes with its own set of challenges. Recycling comprises physical collection and metallurgical processing. Potential sources for recycling include tailings from process scrap used during manufacturing and scrap from end-of-life products.

All the LIBs installed today will eventually reach the end of life depending on the applications. The normal service life for a battery is ~5 years for consumer electronics, ~6 years for small electric mobilities, ~8–10 years for electric vehicles, and ~10 years for energy storage. When these batteries are retired, they can become valuable resources containing considerable amount of lithium, nickel, and cobalt. Especially those LIBs installed in electric vehicles, whose capacities are usually higher than 50 kWh, will cause serious safety and environmental problems if they are not properly disposed. According to the study from Circular Energy Storage (CES) [23], the expected EV battery that will reach the end of life is expected to be 174 GWh worldwide in 2030. This number is even larger than the total installed electric vehicle battery capacity in 2020, which is 136.3 GWh based on GGII data [24]. The expected retired battery amount is listed in Figure 1.15.

While not many electric vehicle batteries have reached the end of their normal life, even fewer of them will eventually be recycled. As more such batteries are retired after mid-century, along with more regulated recycling channels and strict recycling policies and regulations, recycling will be an important addition to the main sources of lithium, nickel, and cobalt. Recycling batteries will help to curb volatility in the supply chain and prices of raw materials or battery manufacturing

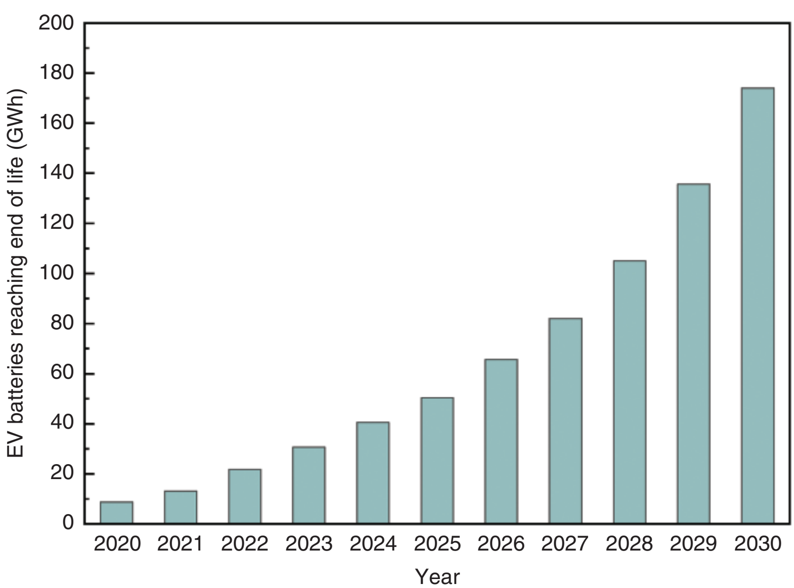

Figure 1.15 EV battery reaching end of life.

and can therefore play a key role in alleviating energy security concerns in countries that rely heavily on imports of these minerals. Based on the recent IEA report, in their SDS scenario, recycling and reuse of EV and storage batteries can reduce the primary supply requirement for minerals by 5% for lithium, 8% for nickel, and 12% for cobalt in 2040 [22].

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