

Review

Comparative Analysis of Cell Design: Form Factor and Electrode Architectures in Advanced Lithium-Ion Batteries

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Abstract

This review investigates how cell form factors (cylindrical, prismatic, and pouch) and electrode architecture (jelly-roll, stacked, and blade) influence the performance, safety, and manufacturability of lithium-ion batteries (LIBs) across the main commercial chemistries LiFePO₄ (LFP), Li (NiMnCo)O₂ (NMC), LiNiCoAlO₂ (NCA), and LiCoO₂ (LCO). Literature, OEM datasheets, and teardown analyses published between 2015 and 2025 were examined to map the interdependence among geometry, electrode design, and electrochemical behavior. The comparison shows trade-offs among gravimetric and volumetric energy density, thermal runaway tolerance, cycle lifespan, and cell-to-pack integration efficiency. LFP, despite its lower nominal voltage, offers superior thermal stability and a longer cycle life, making it suitable for both prismatic and blade configurations in EVs and stationary storage applications. NMC and NCA chemistries achieve higher specific energy and power by using jelly-roll architectures that are best suited for tabless or multi-tab current collection, enhancing uniform current distribution and manufacturability. Pouch cells provide high energy-to-weight ratios and flexible packaging for compact modules, though they require precise mechanical compression. LCO remains confined to small electronics owing to safety and cost limitations. Although LFP's safety and affordability make it dominant in cost-sensitive applications, its low voltage and energy density limit broader adoption. LiMnFePO₄ (LMFP) cathodes offer a pathway to enhance voltage and energy while retaining cycle life and cost efficiency; however, their optimization across various form factors and electrode architecture remains underexplored. This study establishes an application-driven framework linking form factors and electrode design to guide the design and optimization of next-generation lithium-ion battery systems.

Keywords: lithium-ion batteries; cell design formats; form factor; electrode architecture; Tesla 4680 cell; tabless design; cell-to-pack (CTP/CTM/CTC); AZ-stacking; energy density; thermal-runaway; cost



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1. Introduction

Economic development is experiencing rapid growth, leading to increased demand for all types of energy, particularly in the industrial sector. In contrast, the primary source of this energy is fossil fuels [1]. The transportation sector accounts for the largest share 25% of overall consumption, and fossil fuels comprise 90% of this, leading to a rise in carbon

emissions [2,3]. In recognition of the trend and consideration of environmentally acceptable energy options, particularly in transportation, the latter is moving towards electrification.

Lithium-ion batteries (LIBs) provide an outstanding combination of high energy and power density [4,5]. Fierce rivalry among prominent multinational corporations such as CATL, LG Energy Solution, Samsung SDI, Panasonic, BYD, and Tesla has underscored the importance of lithium-ion technology. It is employed in portable electronics and energy storage devices, with considerable emphasis on the electric vehicle sector [6]. LIBs research began in the 1970s, their functional attributes were delineated in 1985, and they were first introduced to the consumer market in 1991, led by Sony [7–9]. Lithium-ion batteries (LIBs) achieved major technological breakthroughs toward the end of the twentieth century, marking a decisive advancement over earlier electrochemical system. Since then, their use has risen sharply, reaching 180 gigawatt-hours (GWh) in 2018 and increasing at an annual rate of about 25% [10]. In that same year, LIBs surpassed lead–acid batteries in overall performance and adoption [11]. By 2024, they had become the dominant technology in the market, with a 75% share in electric-vehicle applications and an energy output exceeding 823 GWh [12]. Looking ahead, global demand is forecast to grow from approximately 1970 GWh in 2025 to about 3910 GWh by 2030 [13]. The reason for employing lithium-ion battery technology is primarily its status as the most electropositive element (-3.04 V relative to the standard hydrogen electrode) and its classification as the lightest metal (Equivalent weight of 6.94 g mol^{-1} and specific gravity of 0.53 g cm^{-3}) [14]. The chemical composition of cathode materials such as LFP, NMC, NCA, LCO, and LMO plays a crucial role in influencing the electrochemical efficiency, safety, lifespan, cost, and ecological impact of lithium-ion batteries [15–17].

The manufacturing of cost-effective cells is a crucial task in electric powertrains. Batteries for electric vehicles account for around 30~40% of the production cost, and the battery cell itself is responsible for about 60~80% of that cost [18]. The impact of various lithium-ion battery designs on manufacturing effort, time, and usage in electric vehicles, storage, laptops, and mobile phones is a common focus of research [19]. Efforts are underway to design batteries with high energy density while maintaining a low cost per kilowatt-hour (kWh). This approach involves enhancing both battery design and cell chemistry. The design phase is crucial from a sustainability perspective, as it emphasizes safety, durability, and cost-effectiveness for manufacturers, while also prioritizing non-polluting, recyclable materials [20–22]. As global research continues to meet demand, lithium-ion battery performance improves year after year, suggesting that the battery cell itself is becoming more efficient and will last at least 30 years, given the availability of basic components in considerable quantities and the lack of alternative solutions on the market [23]. Sodium-ion batteries are under development, but they are still not ready for EV-scale applications due to their low energy density and slow sodium-ion mobility within the cathode materials [24–27].

Over the past few years, demand for lithium-ion batteries has increased significantly, with further growth anticipated in the years to come. Across various fields, including the automotive industry, smartphones, and power tools, it has been observed that products assume different forms based on demand. Regardless of their chemical properties, the primary objective remains to achieve efficiency, reliability, safety, recycling, and sustainability. Determining the ideal geometric shape of the battery depends on its field of use, as each shape has advantages and disadvantages across several criteria, the most important of which are cost and performance [28]. In this review, we will provide a broad overview of various battery designs and their applications, considering performance, efficiency, cost, and safety systems.

2. Lithium-Ion Battery Design Format

2.1. Historical Background

The concept of electrochemical energy storage can be traced back to the first century BC, when the so-called “Baghdad Battery” was discovered in 1936 near Baghdad. This artifact, attributed to the Persian civilization, consisted of an earthenware jar containing a sheet-copper cylinder (98 × 26 mm) sealed at one end with a copper disc. The jar measured 140 mm in height and 80 mm in diameter and was registered under the numbers IM 29209-29211 [29–31].

By the late eighteenth century, Alessandro Volta at the University of Pavia had formally established the electrochemical cell. In 1800, Volta constructed the first true battery, the Voltaic Pile, comprising stacked pairs of zinc and copper discs separated by a saline-soaked electrolyte, which enabled continuous current generation (Figure 1) [32]. Subsequently, in 1801, William Cruickshank improved the design by arranging the electrodes horizontally to form the trough battery (7.62 × 72.39 × 6.35 cm), marking the first device suitable for mass production using zinc–copper plates immersed in a brine or dilute acid electrolyte [33–35].

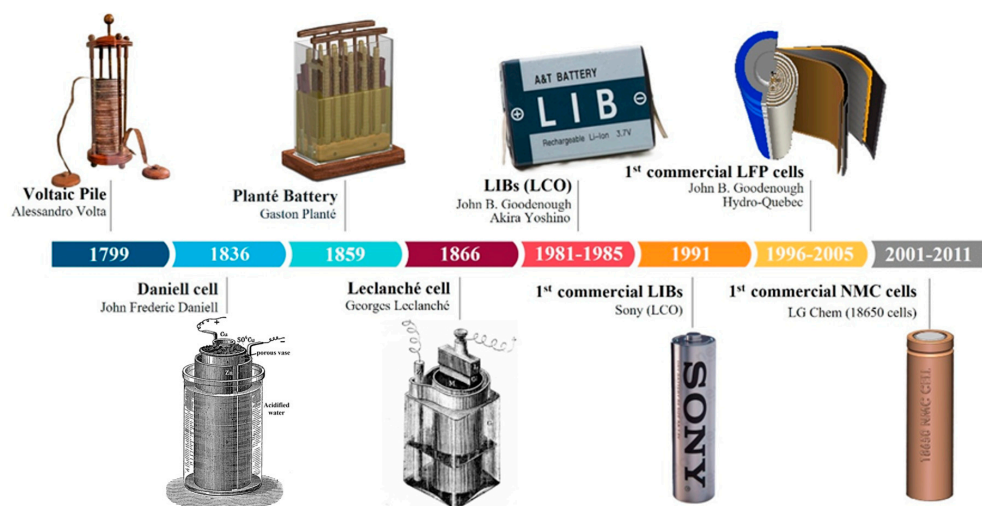


Figure 1. History of batteries and their formats 1799–2011. The following subfigures were used from the references with permission: Diagram showing the components of the Voltaic pile 1799, reproduced with permission [36]; Daniell cell 1836, reproduced with permission [32]; Planté Battery 1859 (Copyright © 2024, National MagLab) [37]; The Leclanché Cell 1866 (Copyright © 2025, Royal Society of Chemistry 2025) [38].

During the first half of the nineteenth century, discoveries in electromagnetism, particularly by André-Marie Ampère (1820) and Michael Faraday (1830), accelerated the development of battery technologies [39–41]. John Frederick Daniell later introduced the Daniell cell in 1836, employing zinc and copper electrodes in their sulfate solutions to produce a stable 1.1 V output. Owing to its improved stability and low corrosion, this cell became widely used in telegraph and early telephone systems [42–45].

In 1866, Georges-Lionel Leclanché advanced the field by creating the Leclanché cell, which utilized a zinc anode and a manganese dioxide-carbon cathode in an ammonium chloride electrolyte, laying the foundation for dry-cell designs [46,47]. Nearly a century later, LiFePO_4 was first identified by Destenay (1950) as part of the olivine-structured lithium orthophosphate series (triphylite-lithiophilite) containing divalent Fe and Mn [48].

Modern lithium-ion battery (LIB) development began in the late 1970s, when a global research effort led to the creation of rechargeable lithium systems [49]. Stanley Whittingham pioneered the use of titanium disulfide and lithium metal electrodes, demonstrating high energy density but raising safety concerns due to lithium reactivity [50–52]. In 1981, John

B. Goodenough introduced lithium cobalt oxide (LCO) as a stable, high-voltage cathode material, significantly improving energy capacity [53]. Later, in 1986, Akira Yoshino replaced metallic lithium with a carbonaceous anode, achieving enhanced safety and stability, and producing the first actual lithium-ion prototype [54,55]. The technology reached commercialization in 1991, when Sony released the first practical lithium-ion battery, featuring a carbon anode, an energy density roughly three times that of nickel-cadmium cells, water resistance, and a lifetime exceeding 1000 cycles [56,57]. Sony's lithium-ion battery chemistry featured an LCO cathode, a carbon anode, and an organic electrolyte composed of LiPF_6 dissolved in a diethyl carbonate/propylene carbonate (DEC/PC) blend. These are examples Sony produced at that time (shown in Table 1) and also display the weight distribution of US-61 cell components in a pie chart [58].

In 1997, Dr. John B. Goodenough and his team at the University of Texas at Austin discovered Olivine as a cathode material for lithium rechargeable batteries [48,59,60]. The same year, LMO was commercialized by Moli Energy (Canada) [61]. In contrast, NMC technology has held a significant share of the battery market since its discovery in 2001 by four research teams. Argonne National Laboratory in the USA is a group led by Michael M. Thackeray [62], Brett Amundsen et al., [63], Jeff Dahn [64], and Tsutomu Ohzuku [65]. This technology made the NMC cathode dominant due to its high voltage, which ranges between 3.6 and 3.7 V [17]. The US Patent was filed by Argonne National Laboratory in the name of Michael M. Thackeray and his team, and it was issued on 13 January 2004 [62]. These inventions triggered a significant shift in the fields of chemistry and electricity, prompting consideration of abandoning fossil fuels, the primary energy source.

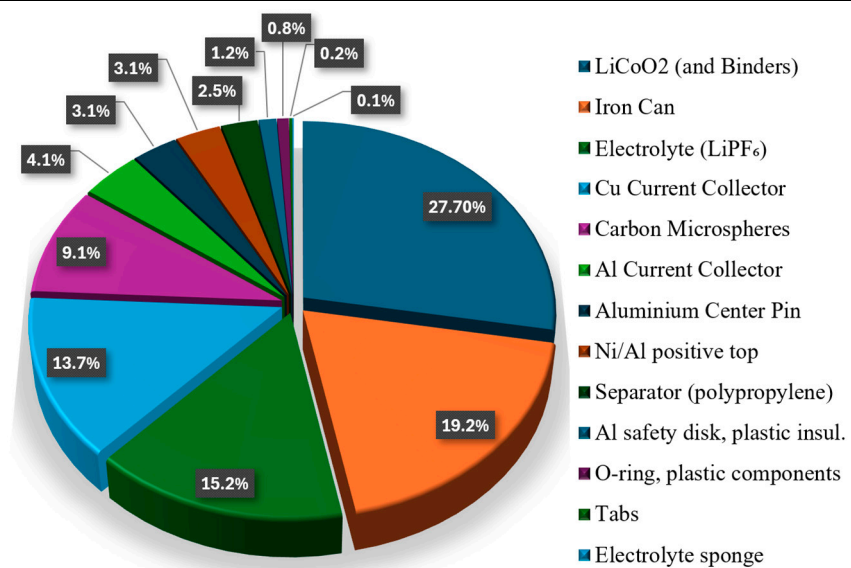
Lithium iron phosphate (LFP) cathode material became available for sale in 2006 when A123 Systems in the USA introduced Nanophosphate[®], particularly in the cylindrical 26650 size for use in power tools and electric vehicles [66], whereas Lithium nickel manganese cobalt oxide (NMC, $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$) saw notable commercialization in 2011, when LG Chem from South Korea supplied NMC-based cylindrical and pouch cells for General Motors' Chevy Volt electric vehicle [67–69].

Table 1. Sony Specification for US-61 Series Cells and Sony Data for the 20500 Cell.

Type of Batteries	US-61 (AA) 14500	US-61 16530	US-61 20420	US-61 20500
Ref. [70]				
Cathode	LiCoO_2			
Electrolyte	LiPF_6			
Anode	Carbon microspheres (Graphite)			
Specific Energy	78 Wh kg^{-1}			
Nominal Capacity (mAh)	400	640	860	1080
Energy Capacity (Wh)	1.44	2.30	3.09	3.89
Nominal Voltage (V)	3.6	3.6	3.6	3.6
Gravimetric Energy Density (Wh kg^{-1})	78	83	98	99
Volumetric Energy Density (Wh L^{-1})	192	204	223	236

Table 1. Cont.

Type of Batteries	US-61 (AA) 14500	US-61 16530	US-61 20420	US-61 20500
Cycle Life (100% DOD)	1200	1200	1200	1200
Operating temperature For Charging (°C)	0~45	0~45	0~45	0~45
Operating temperature For Discharging (°C)	−20~60	−20~60	−20~60	−20~60
Accumulated Dis. Energy Per Volume/weight	199 KWh L ^{−1} 81 KWh Kg ^{−1}	212 KWh L ^{−1} 86 KWh Kg ^{−1}	231 KWh L ^{−1} 102 KWh Kg ^{−1}	245 KWh L ^{−1} 103 KWh Kg ^{−1}
Diameter (mm)	14	16	20	20
Height (mm)	50	53	42	50
Volume (cm ³)	7.5	11.3	13.9	16.5
Mass (g)	18	28	28	39

Sony Lithium-ion US-61
Weight Breakdown

2.2. Types, Structure, and Performance

Battery storage devices consist of electrochemical cells that convert chemical potential to electrical potential during discharge and reverse the process during charging. LIBs have a structured anode (made of graphitic carbon) and a cathode (lithium metal oxide), a separator, and an electrolyte solution (consisting of lithium salts dissolved in inorganic carbonates) [71]. The cathode can be layered, spinel, or olivine structured. By altering the cathode materials in Li-ion batteries, we can further enhance their energy density and efficiency. Batteries are rated by their energy and power capacities [72]. For most battery types, the power and energy capacities are not independent and are specified at the design. Each design offers specific advantages in terms of efficiency, lifespan, operating temperature, self-discharge, and energy density [73].

Lithium nickel cobalt manganese oxide (LiNiMnCoO₂), also known as NMC batteries, among the lithium-ion batteries (LIBs) currently employed in electric vehicles [74], receive excellent evaluations due to their high energy density, exceptional thermal stability, high theoretical capacity (275 mAh g^{−1}), and extended cycle life [75]. Besides the exceptional performance and notable specific energy, which make them an ideal choice for automobile batteries.

NMC cathodes are highly relevant in energy storage technology [76]. However, despite all the latest advances in NMC battery technologies, the vision remains focused on developing lower-cost, environmentally friendly technology and improving the durability of the materials used to manufacture these batteries. As the demand for these batteries grows, concerns arise because the reserves of these raw materials are small [77]. Environmental pollution regulations must be considered due to toxins such as Co and Ni in NMC, which can leak during production and recycling, potentially causing various respiratory ailments [78].

Lithium nickel cobalt aluminum oxide ($\text{LiNi}_x\text{Co}_y\text{Al}_z\text{O}_2$ with $x \geq 0.8$), known as NCA, is called nickel-rich, where $x + y + z = 1$ [79]. NCA batteries offer elevated energy density due to their high voltage and exceptional fast charging capabilities. However, its materials, such as cobalt, are expensive, being significantly more costly than nickel [80]. Moreover, a higher nickel content corresponds to an increase in voltage and the overall capacity the battery can accommodate [81]. The two materials, NCA and NMC, exhibited similar structures and electrochemical characteristics, suggesting comparable performance, particularly in terms of their higher energy and performance metrics [82]. In addition, the presence of aluminum ions in NCA enhances stability and safety while concurrently reducing capacity, as they are less involved in oxidation and reduction processes [83]. Another challenge to this technology is thermal runaway at 180 °C [84,85].

LFP has received extensive research and application interest as a model ionic material with olivine structure and excellent theoretical specific capacity (170 mAh g^{-1}) [86], because of its obvious advantages in terms of the use of raw materials in its manufacture, its cost, light weight, and long service life [87]. All those advantages put LFP as the first choice compared to NMC [88], NCA (LiNiCoAlO_2) [89], Lithium Cobalt Oxide (LiCoO_2), known as LCO [90], and Lithium Manganese Oxide (LiMn_2O_4), known as LMO [91]. The olivine structure of LiFePO_4 (LFP) is hexagonally close packed with oxygen, in which the octahedra share both edges and faces, while the arrangement of cations in LFP differs significantly between layered and spinel structures, such as LCO and LMO [92]. Despite its advantages, such as low cost, low toxicity, greater thermal stability, large specific capacity, ability to hold long voltage plateaus, and structural stability during Li intercalation/deintercalation. LFP suffers from two critical shortcomings: low conductivity ($\sim 10^{-9} \text{ S cm}^{-1}$) and low lithium-ion diffusion capability ($\sim 10^{-14} \text{ cm}^2 \text{ S}^{-1}$) [93]. These drawbacks arise from the absence of a continuous network of FeO_6 edge-shared octahedra which negatively affected its chemical performance and poor conductivity. To overcome these limitations, several strategies have been proposed to improve conductivity and specific capacity, such as carbon coating [48,94]. Furthermore, doping with bivalent cations such as Ni, Co, or Mg into LFP can boost its rate performance by increasing the Li^+ ionic mobility and diffusion coefficient [95].

LiCoO_2 (LCO) batteries were designed to include a high-potential cathode, a low-potential anode, and an electrolyte with a sufficiently wide potential window for successful ion transport [96]. LIBs manufactured by Sony Corporation utilized a graphite anode with a specific capacity of 372 mAh g^{-1} , combined with a LCO cathode, which has a specific capacity of 137 mAh g^{-1} [97]. The electrolyte is comprised by LiPF_6 salt in an EC (Ethylene Carbonate): DEC (Diethyl Carbonate)/DMC (Dimethyl Carbonate) solvent, achieving a working voltage of around 3.0 V, due to its high theoretical density (5.1 g cm^{-3}) and high theoretical capacity (274 mAh g^{-1}) [98,99]. LCO is one of the most promising cathode materials in LIBs and has been accessible for over twenty years; however, it still raises safety concerns due to the inclusion of combustible organic solvents, and its applications remain restricted [100]. LCO has a significantly higher energy density than its size, enabling greater energy storage in a compact, slender device such as an iPod [101]. Additionally, it is available in ultra-thin configurations that complement the sleek look of gadgets and ensure

a stable voltage during discharge [102], making it optimal for audio equipment that requires consistent power to produce sound. The energy density of LCO is 740 Wh kg^{-1} at 4.45 V and increases to 840 Wh kg^{-1} at 4.55 V, which is comparable with Li-rich cathodes [103]. Given that the compressed density of LCO is significantly higher than that of Li-rich cathodes, LCO-based batteries made from lithium exhibit a markedly higher volumetric energy density, an important attribute for power sources in portable devices [104].

LMO batteries provide an average operating voltage of 4.0 V relative to Li/Li⁺, due to the Mn³⁺/Mn⁴⁺ redox couple, with a theoretical gravimetric capacity and energy density of 148 mAh g^{-1} , and superior thermal stability compared to LCO or NCA [17,105–108]. However, the presence of Mn³⁺ ions leads to a Jahn–Teller distortion of the MnO₆ octahedra, resulting in local lattice strain and progressive structural degradation [109]. Moreover, Mn dissolution into the electrolyte during cycling significantly contributes to capacity fading and limits the long-term stability of LMO-based cells [110–113].

The gravimetric capacity of LMO batteries is approximately 130 mAh g^{-1} at low current rates [97,98]. Efforts have been made to enhance the battery's cathode by adding other materials, such as Ni, to form a doped spinel. This doped spinel battery theoretically offers a gravimetric capacity of 161 mAh g^{-1} , but it faces constraints related to thermal stability and recyclability [114,115]. This was a sufficient reason for its limited adoption in electric vehicles.

Solid-state electrolytes (SSEs) and highly nickel-layered cathodes are increasingly acknowledged as synergistic facilitators of next-generation lithium-ion batteries. SSEs, encompassing sulfide, oxide, polymer, and halide systems, yield non-flammable, mechanically resilient ionic conductivity with room-temperature conductivities ranging from 10^{-3} to $10^{-2} \text{ S cm}^{-1}$, thereby enhancing safety and compatibility with lithium-metal anodes [116]. Their mechanical stability enables elevated cathode threshold voltages and facilitates practical energy densities anticipated to surpass 400 Wh kg^{-1} , in addition to enhanced fast-charging capacity [117]. SSE-based architectures can enhance sustainability by minimizing cooling and safety hardware requirements, while facilitating greater lifetime energy throughput through extended cycle lifespans and increased recycling of inorganic electrolyte chemistries [118]. In parallel, high-nickel NMC/NCA cathodes ($\geq 80\%$ Ni) offer higher specific capacity ($>200 \text{ mAh g}^{-1}$) and higher operating voltages, positioning them as crucial components in the development of long-range electric vehicle designs [119]. The reduced cobalt content enhances material sustainability; however, surface reconstruction and microcracking require sophisticated stabilization methods, such as coatings, doping, and single-crystal architectures [120,121]. Recent investigations are delving into the combination of Ni-rich cathodes with sulfide or halide solid-state electrolytes, focusing on how engineered interphases and protective coatings can effectively mitigate degradation and facilitate high-voltage operation (4.3–4.4 V). The integrated materials approach is evident in industrial roadmaps, as leading automakers are set to develop solid-state EV platforms featuring high-energy Ni-rich cathodes by 2027–2028 [122,123].

Currently, the operating voltage and energy density of lithium-ion batteries indicate that LCO, NMC, and NCA batteries provide extended mileage for electric vehicles (EVs) on a single charge, attributed to their superior energy density (shown in Table 2). In contrast, LFP batteries have a lower energy density, which requires electric cars to use more battery cells to meet energy demands, consequently increasing vehicle weight [85]. On the other hand, NMC, LCO, and NCA cells suffer from the problem of thermal runaway (TR), which is a major obstacle in wide applications (EVs, Energy storage), requiring the development of protocols and strategies to prevent TR, such as (cooling-heating) systems, and thus return to the starting point [124,125].

Table 2. Electrochemical performance characteristics of the cathode materials.

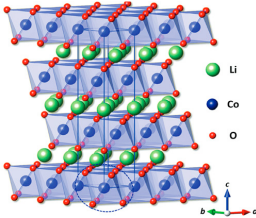
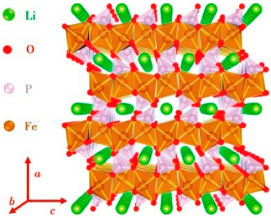
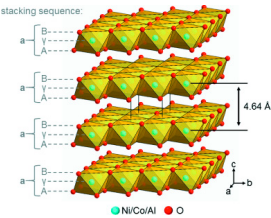
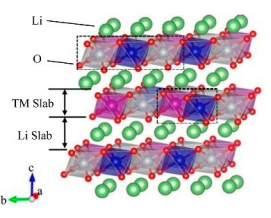
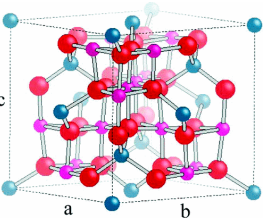
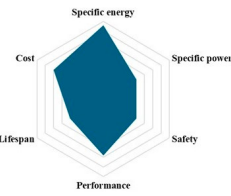
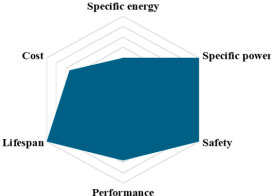
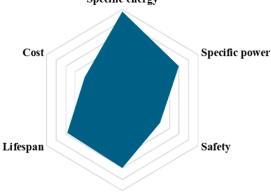
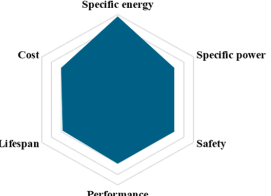
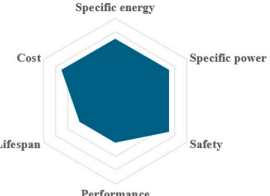
Parameter	LiCoO ₂	LiFePO ₄	LiNi _{0.80} Co _{0.15} Al _{0.05} O ₂	LiNi _{1/3} Mn _{1/3} Co _{1/3} O ₂	LiMn ₂ O ₄	Ref.
Crystal structure of the mechanism						[126–130]
Specific energy Specific power Safety Performance Life span Cost (Radar chart)						[131]
Theoretical Capacity [mAh g ^{−1}]	274	170	279	275	148	[106,107,132,133]
Available Capacity [mAh g ^{−1}]	190@4.45V 215@4.55V	160	200	160@4.3V 185@4.5V	110	[132–134]
Electrode Density [g cm ^{−3}]	3.9	2.3	3.2	3.4	3.2	[106,132]
Galvanometric Energy Density [Wh kg ^{−1}]	740@4.45V 840@4.55V	540	800@4.4V	610@4.3V 730@4.5V	410	[132]
Volumetric Energy Density [Wh L ^{−1}]	2900@4.45V 3300@4.55V	1240	2600@4.4V	2080@4.3V 2480@4.5V	1300	[132]
Operating Voltage [V]	3.9	3.4	3.65	3.8	4.0	[49,98,132]
Application	Mobile phones, tablets, laptops, and cameras	EVs Portable and stationary	Power tools EVs Medical devices	Power tools EVs E-bikes, medical devices	Power tools, medical devices, electric powertrains	[132,135,136]

Table 2. Cont.

Parameter	LiCoO ₂	LiFePO ₄	LiNi _{0.80} Co _{0.15} Al _{0.05} O ₂	LiNi _{1/3} Mn _{1/3} Co _{1/3} O ₂	LiMn ₂ O ₄	Ref.
Advantages	- Fast charging and high energy density. - Established and tested commercial chemistry. - Good cycling performance at operational voltages.	- Relatively economical. - Exceptionally high-speed performance. - No resource constraints. - Extremely sluggish response with electrolyte. - Outstanding safety (no oxygen emission).	- Performance is well established. - Delayed response with electrolytes. - High capacity. - Excellent high-rate performance.	- High capacity. - High operational voltage. - Gradual interaction with electrolytes. - Moderate safety (oxygen emission).	- Economical. - Superb high-rate efficacy. - Elevated operating voltage. - No constraints on resources. - Moderate safety (oxygen emission).	[81,137–139]
Disadvantages	- Thermal instability. - Limited practical capacity compared to theoretical potential. - High cost of cobalt and associated supply and ethical concerns. - Performance constraints at elevated voltage or prolonged cycling.	- Decreased operating voltage - Limited capacity, mainly for substituted models. - Regulating patents.	- Expensive Ni and Co. - Possible resource constraints. - Controlling safe patents.	- Expensive Ni and Co. - Possible resource constraints - Emerging in performance. - Controlling patents.	- Mn solubility influences cycle life. - Low capacity.	[81,137,140,141]

3. Cell Design Technologies

Since the beginning of battery development, this phase has aligned with their practical applications in everyday life, leading to a variety of specific cell designs. Battery manufacturers are currently exploring several cell and battery design concepts. Extensive prior research indicates that the precise design of the battery does not substantially influence the cost of a particular cell chemistry system; rather, the quantity of electrode materials and the number, capacity, and dimensions of the cells are the main determinants of pricing [142]. Cylindrical wound cells are the predominant design for batteries in large-scale production and are considered the first commercial battery in history, manufactured by Sony. We previously discussed the introduction of the first series of cells, the US-61 series, to the market (Table 1), along with the 18650. Initially, mobile phones and handheld video cameras used it. Then, the prismatic [9,143], and the blade cells [144] emerged by 2020.

Understanding how different battery designs work and perform gives us important insights into battery systems [145]. The key difference between cell types lies in how the cell casing is made and how the cathode, anode, and separators are arranged. Individual cell design can take various forms. This flexibility enhances the applicability of Li-ion batteries, enabling them to be tailored to multiple form factors to meet specific requirements [146]. Prismatic and cylindrical cells are the construction of the cell casing, which is encased in a rigid case, generally made from aluminum or stainless steel (shown in Figure 2).

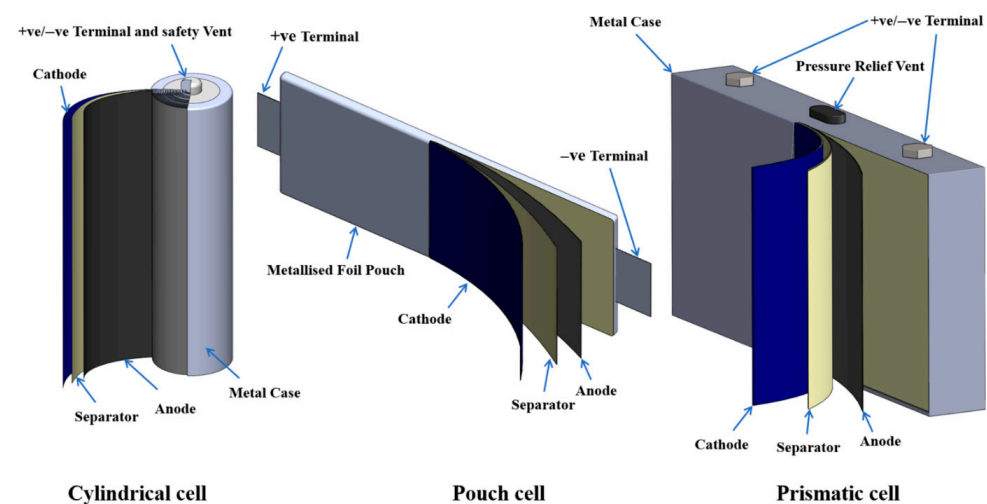


Figure 2. Comparison of Lithium-ion Cell Formats: Cylindrical Vs. Pouch Vs. Prismatic.

Pouch cells are encapsulated in multilayer aluminum composite foils. Cylindrical cells consist of electrode webs wound with separators to form a jelly roll structure, while prismatic cells use either flat jelly rolls or stacked electrodes. In contrast, pouch cells rely exclusively on a stacked configuration (Table 3) [146,147]. Regardless of cell shape, the manufacturing process can be divided into three main stages: the initial stage involves electrode production, followed by cell assembly. These two stages encompass all cell types, with the sole distinction being the techniques employed for formation and finishing, which constitute the final stage of production [148].

Table 3. Cell designs, along with their respective strengths and weaknesses.

Shape	Cylindrical	Prismatic/Blade	Pouch	Ref.
External shape	Cylindrical Box metal casing	Rectangular box (Rigid metal casing)	Polymer–aluminium laminate	[149]
Electrode arrangement	Wound (jellyroll)	Stacked /flat Jelly rolls	Stacked	[146,149,150]

Table 3. *Cont.*

Shape	Cylindrical	Prismatic/Blade	Pouch	Ref.
Mechanical strength	Excellent	Very Good	Medium	[149,150]
Thermal Management	Medium	Good	Good	[146,150]
Specific Energy (Wh kg ^{−1})	Good	Good	Excellent	[146]
Volumetric Energy Density (Wh L ^{−1})	Good	Excellent	Good	[146,149]
Pack Integration Efficiency (CTP/CTC Compatibility)	46xx Cell: Good Small size: Medium (requires modules or honeycomb structures → reduces CTP efficiency)	Prismatic: very good Blade: Excellent (extremely optimized for CTP/CTC)	Good in CTP (but requires external compression frames and thermal barriers)	[151–153]

Determining the optimal battery configuration for a given application is crucial to any project. The manufacturer's selection of a specific shape is intricately linked to the system's corresponding advantages and shortcomings and is informed by factors such as cost and performance. However, their motivations are often veiled behind commercial secrecy. This strategy is advantageous from a commercial standpoint. However, it results in fragmented information about batteries in literature. This field of study aims to assess the electrochemical and mechanical performance of each geometry and its scope of use.

The cell assembly stage is the most critical phase of battery manufacture, following validation of its electrochemical efficiency. Mechanical engineering is incorporated into the design phase through assembly methodologies. Winding for cylindrical and prismatic cells (Figure 3a,d) and stacking for pouch cells (Figure 3b,c) are essential components of the cell assembly process for lithium batteries [154]. Although the winding method is well-established, cost-effective, and boasts a high yield rate, it requires a longer development time [155,156]. In addition, the stacking battery differs from the winding in that it is a manufacturing procedure involving pole pieces and separators [157]. When it comes to improving electric vehicles, the contrast between stacking batteries and winding shows that stacking batteries has become more popular (as shown in Figure 3) [158]. This is because it offers several benefits, including the ability to handle high volumes, stability, low internal resistance, and long-lasting performance.

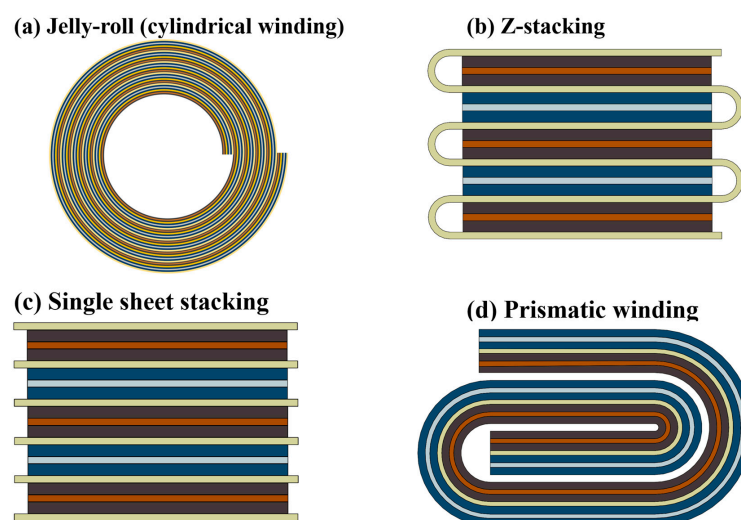


Figure 3. Schematic demonstrating four major lithium-ion cell manufacturing methods. (a) Jelly roll (cylindrical cell); (b) Z-stacking; (c) single-sheet stacking; and (d) prismatic winding.

3.1. Cylindrical Cells Format

Based on the 18650-type cylindrical batteries marketed, LIBs have steadily improved in energy density since their initial use in the early 1990s [159]. This type of rechargeable battery is among the most widely used [160]. The cylindrical form was first designed for consumer electronics, but its remarkable scalability, strong mechanical stability, and efficient production made it ideal for industrial applications, ESS, and EVs. The fundamental design of a cylindrical cell consists of a metal container (typically stainless steel or aluminum) that encloses a jelly roll, a spirally coiled assembly that includes the cathode, anode, and separator layers [150]. The electrodes are double-sided coated on current collectors [161], commonly aluminum foil for the cathode and copper foil for the anode and are then woven together using a microporous polymer separator designed to prevent internal short circuits [107,161,162].

The entire assembly is placed into a cylindrical shell and filled with a liquid electrolyte, typically a lithium salt such as LiPF_6 dissolved in organic solvents, including ethylene carbonate (EC) and dimethyl carbonate (DMC) [163]. The jelly-roll design optimizes the surface area available for electrochemical processes within a given cell volume, thereby enhancing energy density and power density [164]. The spiral symmetry facilitates uniform current distribution and effective heat dissipation during rapid charge and discharge cycles. The implementation of double-sided coating on aluminum foil for cathodes and copper foil for anodes represents a pivotal design approach in the manufacturing of lithium-ion cells. This strategy markedly boosts energy density, reduces the weight of current collectors, enhances mechanical strength during jelly-roll winding compared to single-sided designs, improves thermal dissipation, and supports cost-effective, high-throughput production [161,165].

Due to their ease of manufacturing and low cost, cylindrical L-ion cells have gained tremendous popularity, particularly in the automotive industry. The 18650 cell ($D = 18 \text{ mm}$; $L = 56 \text{ mm}$) was a key component in early EVs, with a typical capacity around 3 Ah [166]. Then, the NCA-21700 ($D = 21 \text{ mm}$; $L = 70 \text{ mm}$) lithium-ion cell was first introduced by Tesla and Panasonic in 2017 [167]. Used in the Tesla Model 3, the 21700 provides ~46% more volume than the 18650, enabling higher capacity 4000~5000 mAh, greater energy density, and improved safety [168,169]. Three years later (22 September 2020), Tesla introduced the first NMC811-4680 battery ($D = 46 \text{ mm}$; $L = 80 \text{ mm}$) [147], 5.5-fold the size of its predecessor (Shown in Figure 4). The 46120 designation indicates a diameter of 46 mm and a height of 120 mm, resulting in greater energy output per cell relative to shorter designs [170]. BYD is among the initial makers of the 46120 formats, having launched the FC46120P LiFePO_4 cell with a nominal capacity of approximately 24–25 Ah and a nominal voltage of 3.2 V [171,172]. Following the announcement by the Fraunhofer Institute for Systems and Innovation Research, it is expected to save up to 20% of manufacturing costs by increasing the cell height from 4680 to 46120 through the adoption of LFP chemistry [173].

The energy density calculations for 21700 and 4680 cells are based on commercialized cell designs and on data published by OEMs on their proposed first-generation tabless cylindrical cells [176]. The 4680 designs, published by Tesla, feature an energy density comparable to that of existing 21700-type cells [177,178]. As is the case with the BMW Group, they have recently started production of a model (Neue Klasse, 6th Generation) use 46 mm diameter cylindrical cells in two heights: 95 mm and 120 mm (“4695” and “46120” formats), which have an energy density ~20% higher than that of the 5th generation prismatic cells [179,180]. One of the most significant improvements of this generation is fast charging capability, which is ~30% more efficient than its predecessor [181]. BMW has announced plans to integrate lithium-iron-phosphate (LFP) chemistry into its 4680 cells; a move aimed at enabling the production of more affordable EVs [182]. By adopting

LFP, BMW can reduce its reliance on essential raw materials such as cobalt and nickel, thereby improving its environmental impact while ensuring ethical sourcing for its battery manufacturing processes [183]. In response to the expected demand for these advanced cells, BMW has proactively established supply partnerships with two prominent battery manufacturers, CATL and EVE Energy [184].

Mass production began in early 2022, primarily at the Tesla Kato Road facility in California and at Giga Texas [174]. This expansion contributed to Tesla achieving the highest Model Y sales in 2022 [175]. The larger batteries enable assembly with fewer cells, reducing costs.

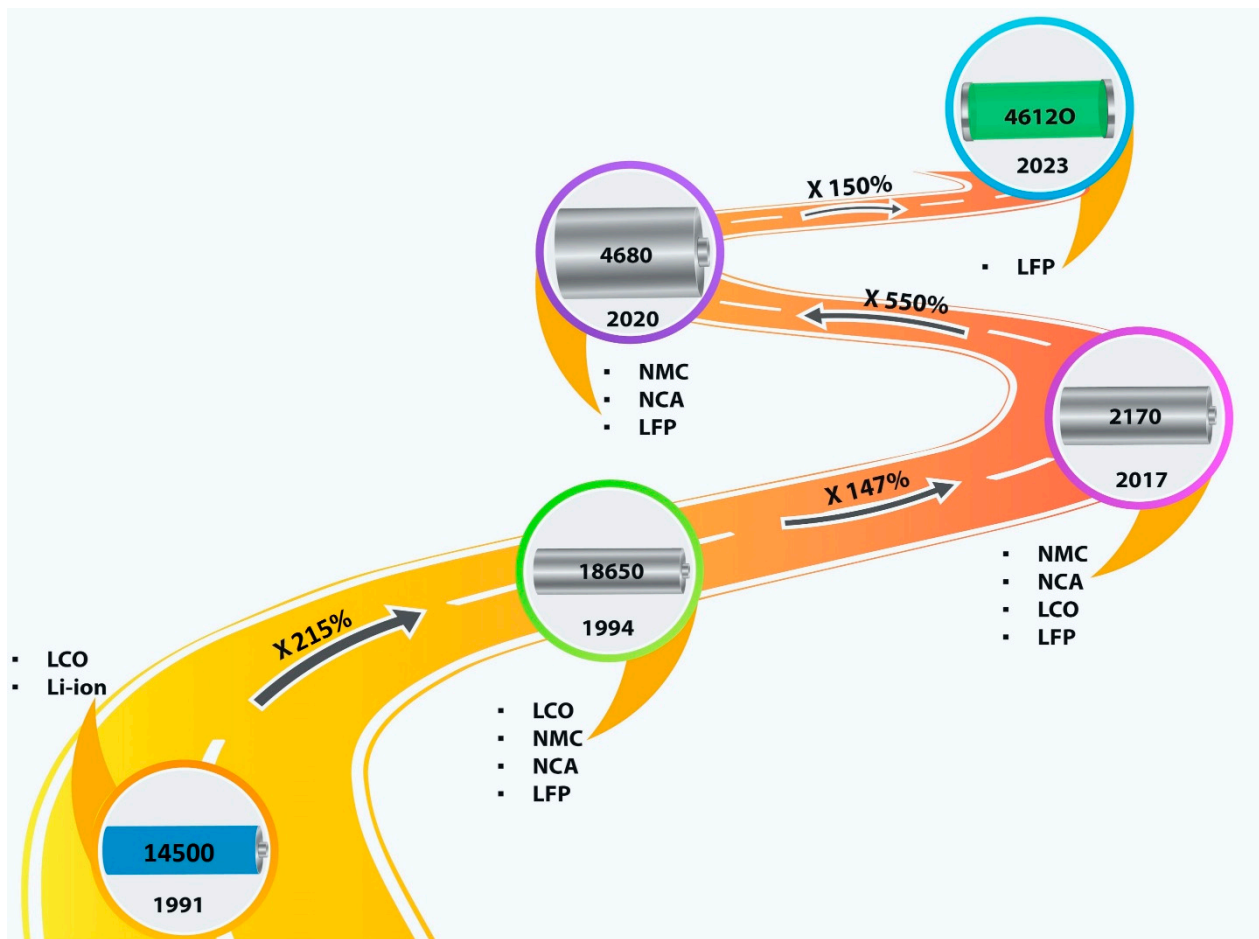


Figure 4. Cylindrical cell format evolution by year and size (1991–2023).

To enhance our understanding of cylindrical cell design characteristics, Table 4 presents an analysis of 25 cells across the most widely used formats over the past decade. The selection includes 18500, 18650, 20700, 21700, 26700, 4680, and 46120 cells from eight established manufacturers (Panasonic, LG, Molicel, Samsung SDI, Tesla, BYD, A123 Systems, and Sony). We collected data for each cell and studied its field of use using the Batemo Cell Explorer and the manufacturer's data sheets [185–190]

Table 4. Analysis of the most prevalent cylindrical cells and their market impact.

Manufacturer	Model	Chemistry	Dimension (mm)	Nominal Voltage	Capacity (Ah) Nominal/C/10	Energy Density (Wh kg ⁻¹)/(Wh L ⁻¹)	Power Density (W·kg ⁻¹)/(W·L ⁻¹) (Continuous)	Power Density (W·kg ⁻¹)/(W·L ⁻¹) (Peak)	Weight (g)
 Panasonic	NCR18500A	NCA	18 × 49	3.6	2.04/2.00	222/585	520/1339	935/2406	32.1
	NCR18650-A	NCA	18.1 × 64.7	3.6	3.07/2.98	242/649	326/877	772/2078	44.8
	NCR18650-B	NCA	18.2 × 65.1	3.6	3.35/3.28	262/704	357/962	789/2126	45.6
	NCR18650-G	NCA	18.3 × 65.1	3.6	3.40/3.34	264/720	399/1080	778/2108	46.4
	NCR2070-C	NCA	20 × 69.4	3.6	3.62/3.25	197/547	1224/3430	1718/4770	61.1
	TESLA Model S	NCA	18.2 × 65	3.6	3.40/3.22	253/692	401/1106	945/2602	46.6
	NCR2170-M	NCA	20.9 × 70	3.6	5.02/4.98	271/755	318/887	842/2344	66.9
	TESLA Model 3	NCA	21 × 70	3.6	4.80/4.66	250/707	350/990	943/2664	68.5
	TESLA Model Y	NCA	20.9 × 70.1	3.6	4.60/4.50	242/689	391/1114	939/2678	68.6
 LG	INR18650-MJ1	NMC	18.2 × 65	3.6	3.50/3.23	255/705	430/1189	916/2531	46.7
	INR21700-M50LT	NMC-811	21.1 × 70.3	3.63	4.80/4.79	263/723	529/1456	1111/3059	67.7
	INR21700-M50U	NMC-811	21 × 69.9	3.6	5.00/4.67	250/707	385/1090	898/2544	68.6
	INR21700-M48	NMC-811	21 × 70	3.63	4.80/4.58	252/700	360/997	891/2468	67.3
 MOLICEL®	INR-21700-M65A	NMC	21.55 × 70.21	3.6	6.5/6.4	322/943	546/1500	1040/2858	74.5
	INR-21700-P60B	NMC	21.35 × 70.13	3.6	5.85/6	280/888	2880/8600	4800/14,300	75
 SAMSUNG SAMSUNG SDI	INR18650-35E	NCA	18.5 × 65	3.6	3.30/3.32	251/695	546/1500	1040/2858	48.0
	INR21700-50S	NMC	21.1 × 70.6	3.6	5.00/5.04	260/742	817/2331	1430/4088	70.6
	INR21700-50G	NMC	21.1 × 70.4	3.63	5.00/4.87	259/722	416/1162	962/2691	68.8
	INR21700-53G (1)	NMC	21.2 × 70.7	3.6	5.30/5.12	265/749	435/1230	970/2740	70.5
 TESLA	Tesla Model Y (4680)	NMC-811	45.9 × 79.8	3.63	22.0/22.5	233/622	369/1000	836/2265	358.0
 BYD	FC4680	LFP	46.1 × 80.1	3.2	15/15.2	150/367	282/693	661/1625	328.5
	FC46120P	LFP	46.2 × 119.2	3.2	24.5/24.1	172/392	820/1869	1263/2880	455.3
 A123 ENERGY SOLUTIONS	26700 NCA GL	NCA	25.8 × 69.5	3.6	3.30/3.42	143/341	231/556	6085/14,660	87.6
 SONY	UR18650-ZM2	NCA	18.3 × 64.4	3.6	2.55/2.56	214/558	452/1182	912/2380	44.2
	US21700-VTC6A	NMC	21.3 × 69.9	3.6	4.00/3.76	187/549	900/2643	1450/4259	73.1

Table 4. Cont.

Manufacturer	Model	Chemistry	Dimension (mm)	Nominal Voltage	Capacity (Ah) Nominal/C/10	Energy Density (Wh kg ⁻¹)/(Wh L ⁻¹)	Power Density (W·kg ⁻¹)/(W·L ⁻¹) (Continuous)	Power Density (W·kg ⁻¹)/(W·L ⁻¹) (Peak)	Weight (g)
Model	Voltage range (V)	Current (A) Continuous/Peak	Energy _{c/10} (Wh)	Power (W) Conti/Peak	Temperature range	Current range (A) Discharge/charge SoC range (0–100%)	Application		
NCR18500A	2.5–4.2	5.04/9.13	7.31	16.7/30	−20~60 °C	(−10 A/3 A) [−5 C~1.5 C]	power tools, low-profile battery		
NCR18650-A	2.5–4.2	4.39/10.4	10.8	14.6/34.6	−20~60 °C	(−15 A/5 A) [−5 C~1.0 C]	Laptops, low-power tools,		
NCR18650-B	2.5–4.2	4.89/10.9	12.0	16.3/36.0	−20~60 °C	(−17 A/7 A) [−5 C~2.0 C]	High-Energy laptops, power banks		
NCR18650-G	2.5–4.2	5.51/11.0	12.3	18.5/36.1	−20~60 °C	(−12 A/7 A) [−3 C~2.0 C]	Consumer electronics, backup power		
NCR2070-C	2.5–4.2	22.0/31.0	12.0	74.8/105	−20~80 °C	(−109 A/14 A) [−30 C~4.0 C]	Industrial tools, high-power flashlights		
TESLA Model S	2.5–4.2	5.38/12.3	11.8	18.7/44.0	−20~60 °C	(−17 A/7 A) [−5 C~2.0 C]	Tesla EV battery packs (older generation)		
NCR2170-M	2.5–4.2	6.12/15.8	18.1	21.3/56.3	−20~60 °C	(−18 A/5 A) [−4 C~2.0 C]	EV battery modules, grid storage		
TESLA Model 3	2.5–4.2	7.01/17.8	17.1	24.0/64.6	−20~60 °C	(−19A/10 A) [−3 C~1.0 C]	Tesla Model 3 battery pack		
TESLA Model Y	2.5–4.2	7.68/18.1	16.6	26.8/64.4	−20~60 °C	(−23 A/9 A) [−5 C~2.0 C]	Tesla Model Y battery pack		
INR18650-MJ1	2.5–4.2	5.98/12.2	11.9	20.1/42.8	−20~60 °C	(−14 A/5 A) [−4 C~2.0 C]	Laptops, energy storage systems		
INR21700-M50LT	2.5–4.2	10.3/21.4	17.8	35.8/75.2	−20~70 °C	(−24 A/10 A) [−5 C~2.0 C]	EV modules, energy storage, e-scooters		
INR21700-M50U	2.5–4.2	7.83/17.8	17.1	26.4/61.6	−20~70 °C	(−20 A/5 A) [−4 C~1.0 C]	Power tools, e-mobility, consumer packs		
INR21700-M48	2.5–4.2	6.90/16.7	17.0	24.2/59.9	−20~60 °C	(−19A/10A) [−4 C~2.0 C]	E-bikes, portable storage, mild-drain tools		
INR-21700-M65A	2.5–4.2	26/50	23.4	93.6/180	−40~60 °C	(−20 A/6 A) [−4 C~2.0 C]	E-bikes, power tools, drones, BEV		
INR-21700-P60B	2.5–4.2	60/100	21.6	216/360	−40~60 °C	(−60 A/6 A) [−10 C~1 C]	Drones & eVTOLs, Motorcycle racing		
INR18650-35E	2.5–4.2	7.80/14.6	12.1	26.2/49.9	−20~70 °C	(−19 A/10 A) [−4 C~2.0 C]	E-bikes, light EVs, battery packs		
INR21700-50S	2.0–4.2	16.9/29.2	18.3	57.6/101	−20~80 °C	(−100 A/20 A) [−20 C~4.0 C]	High-performance EVs, power tools		
INR21700-50G	2.5–4.2	8.24/18.5	17.8	28.6/66.2	−20~60 °C	(−20 A/10 A) [−4 C~2.0 C]	EV battery packs, UPS systems		
INR21700-53G (1)	2.5–4.2	8.85/19.5	18.7	30.7/68.4	−20~60 °C	(−27 A/11 A) [−5 C~2.0 C]	Power tools, heavy EV modules, Drones		
Tesla Model Y (4680)	2.5–4.2	37.7/88.7	83.3	132/299	−10~60 °C	(−220 A/88 A) [−5.5 C~2.0 C]	Tesla structural battery pack (Model Y)		
FC4680	2.0–3.65	30.8/76.9	49.1	92.5/217	−20~60 °C	(−83 A/30 A) [−10 C~4.0 C]	BYD Blade battery for EVs (LFP chem)		
FC46120P	2.0–3.65	124/196	78.4	373/575	−20~60 °C	(−221 A/49 A) [−9 C~2.0 C]	BYD stationary storage & EV platforms		
26700 NCA GL	2.5–4.2	5.49/148	12.5	20.2/533	−20~75 °C	(−363 A/302 A) [−110 C~90.0 C]	High-power tools, military-grade devices		
UR18650-ZM2	2.5–4.23	5.83/11.7	9.46	20/40.3	−20~60 °C	(−13 A/5 A) [−5 C~2.0 C]	Consumer electronics, light tools		
US21700-VTC6A	2.5–4.2	20.2/30.7	13.7	65.8/106	−20~80 °C	(−80 A/16 A) [−20 C~4.0 C]	High-performance UAVs, power banks		

Cylindrical LIBs are available in 18650, 21700, and 4680 sizes, making them suitable for a range of electronic devices and EVs [191]. Their sturdy metal shell and symmetrical shape make them stable against temperature fluctuations and effective at dissipating heat [192]. They offer a long cycle life, stable electrochemical performance, and are simple to handle and integrate into modular pack designs [193–195]. The disparities in energy density found in commercial 18650 lithium-ion cells from manufacturers such as Panasonic, LG Chem, Samsung, and Sony (Murata) can be attributed to several interrelated factors, including differences in the cathode chemistry, improvements in electrode engineering, and in electrolyte composition, innovations in internal cell design, and distinct methodologies employed by each manufacturer. Panasonic's NCR series, utilizing high-nickel NCA chemistry, consistently achieves remarkable gravimetric energy densities of 271 Wh kg^{-1} , with volumetric densities exceeding 755 Wh L^{-1} (Table 3; NCR2170-M cells). This renders them especially appropriate for rigorous applications, including electric vehicles and power equipment. LG Chem's NMC-based cells, including the MJ1 and M50LT, have similar energy density (up to 263 Wh kg^{-1}), though they exhibit slightly lower peak power efficiency. Samsung SDI's INR21700-50S excels in the power sector, achieving peak power densities of up to 4088 Wh L^{-1} due to its enhanced internal resistance and electrolyte composition. Meanwhile, Sony's US21700-VTC6A records one of the highest peak power densities noted (1450 Wh kg^{-1} ; 4259 Wh L^{-1}), establishing it as a standard for high-rate discharge applications [196].

Variations in composition affect lithium intercalation capacity, the operating voltage range, and thermal stability, each of which directly affects energy output. Furthermore, variations in electrode design among companies lead to differences in energy density. By optimizing electrode thickness and porosity, it is possible to achieve higher energy storage [197]. However, thicker electrodes must maintain a careful balance between conducting ions and mechanical integrity. Molicel's INR-21700-M65A/P60B is a high-performance hybrid that combines outstanding energy density with continuous power capability, making it ideal for demanding applications that require both capacity and current. The Molicel INR-21700-M65A is optimized for high energy density and extended runtime under moderate loads, whereas the INR-21700-P60B prioritizes high-current, high-power performance at the expense of a slight reduction in energy density for demanding applications [188–190]. In contrast, Tesla's 4680 cell, although it has a lower gravimetric energy density of approximately 233 Wh kg^{-1} , prioritizes scalability, thermal efficiency, and manufacturability in its large-format cylindrical design [177]. A123's NCA-based 26700 cell is designed for high-voltage pulse applications, reaching exceptionally high peak volumetric power (up to $14,660 \text{ Wh L}^{-1}$) while maintaining a modest energy density of approximately 143 Wh kg^{-1} (see Table 4; 26700 NCA GL).

NMC and NCA cells dominate the market [181], despite the multiplicity of companies operating in this field; for example, 18650 cells have gained wide application due to their small size and excellent chemical and mechanical properties. In comparison, 21700 and 4680 cells accounted for the largest share in the field of electric car manufacturing [198]. The size and shape of a battery for an electric vehicle are crucial factors that impact on the energy capacity of the cells, the range of applications, and the overall cost.

The 4680 cylindrical cells have varied dimensions across manufacturers. Tesla uses NMC cells, whereas BYD uses LFP cells of the exact dimensions. Manufacturers rely on the strength of each cell, particularly its chemical properties. As previously noted, NMC cells exhibit greater capacity and energy density compared to LFP cells. However, when evaluating the reliability, longevity, and affordability of LFP cells, the situation presents a different perspective. Aside from the challenges of energy loss when charging and discharging, LFP cells possess a significant advantage over NMC cells. Tesla's use

of a tabless design has reduced the manufacturing costs of NMC cells; however, these prices remain relatively high compared to BYD's LFP batteries. Tesla's tabless design still enhances charging performance by reducing polarization and ohmic heating compared to earlier 18650 and 21700 cell designs (shown in Figure 5). It also improves cell uniformity, thereby facilitating format and the independent scaling of fast-charging performance when using tab-cooling topology [177]. The electrode wafers are laser-cut and directly connected around the perimeter of the jelly-roll, with the entire wafer acting as a continuous tab, thereby reducing the length of the electrical path (Figure 6a–c). This design offers several advantages, including lower internal resistance and more direct and uniform current flow, resulting in less ohmic heating. It also enables higher continuous power and improved thermal management consistency, allowing for faster charging and discharging, as well as simplified manufacturing, resulting in increased production at lower costs [170,199].

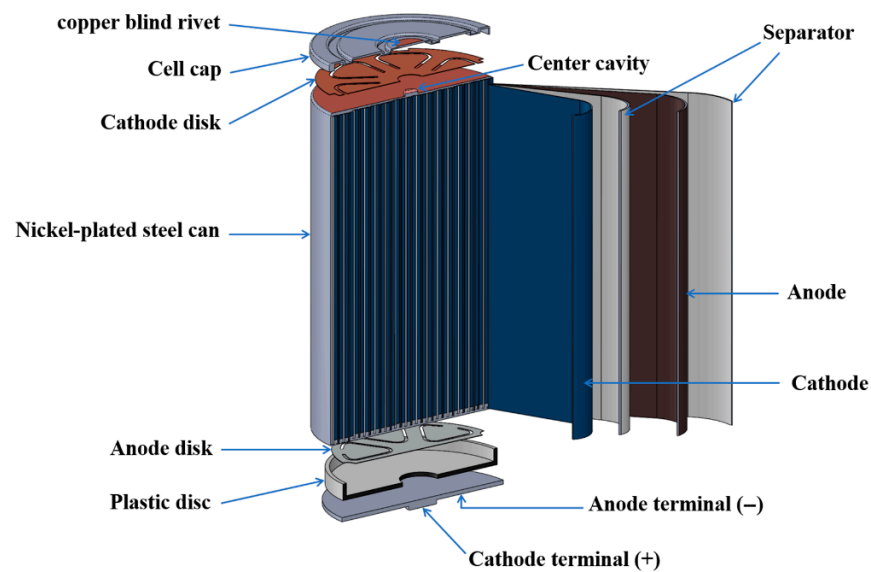


Figure 5. Longitudinal section of cylindrical cell (Tesla 4680) components.

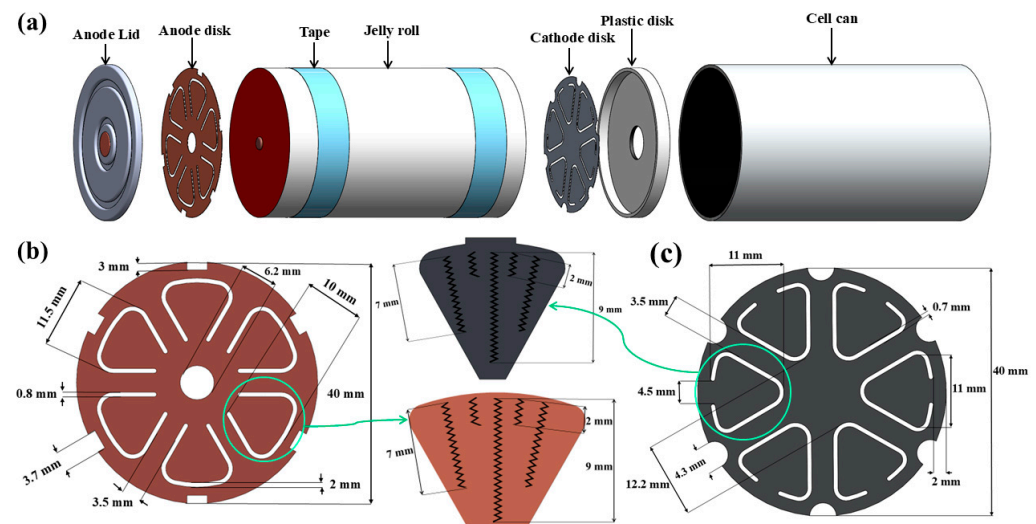


Figure 6. (a) Detailed drawing of the parts of a 4680 cell, taken from the reel dimensions of the cell, current collector disks, and the jelly-roll; (b,c) The measurements of the cathode disk and the anode disk provide a detailed view of the leaf-formed connectors, as well as the dimensions and configuration of the laser welds. Data reproduced from [177].

The FC46120P batteries deliver significantly more power, up to 10 times that of standard 21700 cells. They also offer superior manufacturing efficiency, lower production costs, better thermal dissipation, and faster charging rates. It also significantly improves cycle life performance and energy density. Additionally, employing a full-tab (non-polar tab) design reduces the electron's path within the cell, resulting in lower internal resistance and improved charging and discharging performance [200]. The LFP sector is anticipated to see the most rapid expansion throughout the forecast period owing to its cost-effectiveness, extended cycle life, and intrinsic safety features [87,201,202].

The differences we observe indicate that deliberate choices are being made. For instance, high-energy cells prioritize larger electrodes and high-nickel chemistry to enhance capacity. Increasing capacity is the primary goal of high-energy cells, which prioritize larger electrodes and high-nickel chemistry. In contrast, high-power cells improve stability at high temperatures by reducing internal resistance. Thanks to this, they can charge rapidly and manage high loads with ease. There is no universally optimal cell design; instead, selection must be based on the intended function. Products are manufactured to meet the demands of several sectors, including EVs, electronic gadgets, the aerospace sector, and stationary storage systems.

3.2. Prismatic Cells Format

Prismatic lithium-ion batteries (LIBs) have been recognized as highly effective energy sources for electromobility applications, primarily because of their efficient use of space. They are characterized by their flat shape and are contained in durable stainless steel or aluminum casings; their electrodes are stacked or flat-coiled [162,203], unlike jelly roll-shaped cylindrical cells [164,204]. This design enables enhanced packaging flexibility and a more efficient utilization of space within battery modules.

Prismatic cells optimize volumetric energy density through a compact rectangular design that minimizes void space. Prismatic cells utilize approximately 90% of their box volume, in contrast to cylindrical cells, which lose around 21.5% of their bounding volume (shown in Figure 7). This efficiency makes prismatic cells especially suitable for situations where saving space and weight is essential, such as in electric vehicles (EVs) and energy storage systems (ESS) [205]. This technology delicately balances energy density, thermal resistance, and long-term cyclability, enabling more compact and structurally integrated battery pack designs that meet the evolving needs of high-performance, space-saving, and sustainability-focused energy systems. However, it may incur higher manufacturing costs, exhibit lower thermal management efficiency, and have a shorter lifespan compared to the cylindrical design [206].

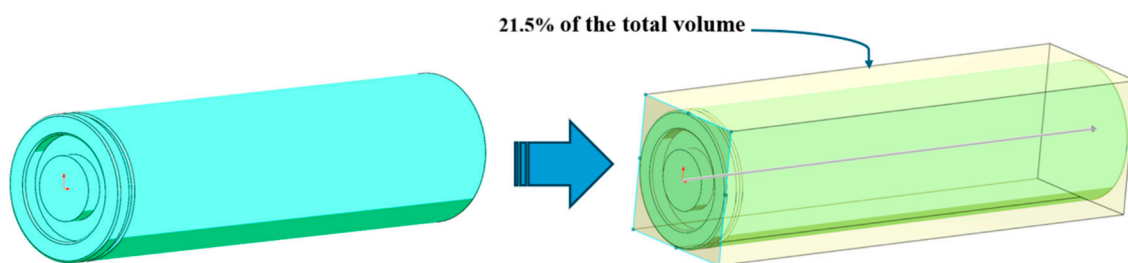


Figure 7. Volume loss of cylindrical cells in large applications compared to prismatic cells.

The manufacturing stages of prismatic cells follow the same pattern as cylindrical cells in preparing the active material mixture. Regardless of the type of active material, the coating of this mixture occurs on both cathodes and anodes, under different coating conditions (as shown in Figure 8a–d), thereby maximizing the surface area of the electrodes.

During the stacking phase, layers of anode, separator, and cathode are organized using either Z-folding or flat-stacking to form the cell's core. The electrode stack is then affixed to current collectors using ultrasonic or laser welding, establishing electrical connectivity with the cell terminals [207].

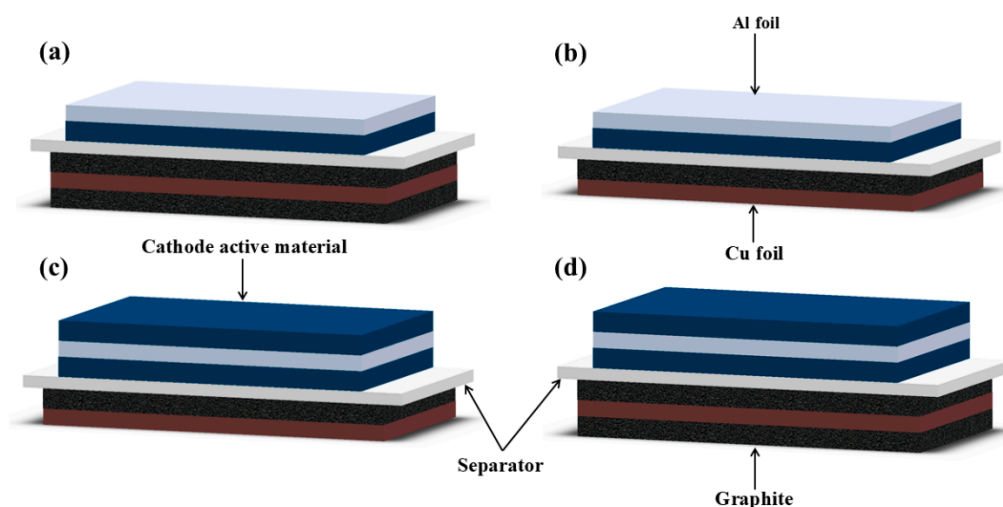


Figure 8. A schematic illustration of different types of case design: (a) single-side-coated cathode/double-side-coated anode, (b) single-side-coated cathode/single-side-coated anode, (c) double-side-coated cathode/single-side-coated anode, and (d) double-side-coated cathode/double-side-coated anode [161].

The cell housing material includes a tri-layer structure: an outer layer made of polyethylene terephthalate (PET) for enhanced strength, an intermediate layer of 0.1~0.2 mm aluminum that provides stiffness and acts as a barrier against moisture and solvent vapors, and an inside layer constructed from polypropylene (PP) that is engineered for sealing via heating [208,209].

The designation “prismatic cell” is intimately linked to CATL (Contemporary Amperex Technology Co., Limited, China), the largest global producer of batteries for electric cars and energy storage, with a worldwide market share of 37.9% in 2024, followed by BYD with 17.2%, according to data published by the South Korean market research company SNE Research [210]. In contrast to cylindrical battery designs, which predominantly utilize NMC, prismatic cells primarily employ LFP as their cathode material. While the energy density of LFP is approximately 43% lower than that of NMC, several critical factors determine cell chemistry. LFP technologies are noted for their low manufacturing costs [211,212], reliability, long life cycle [87,201,202,213], and the absence of toxic metals like nickel and cobalt [214], as well as their safety across various applications [215].

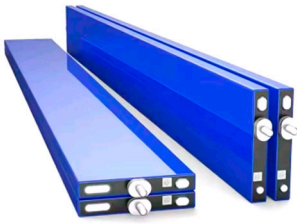
For the past ten years, cylindrical lithium-ion batteries have been the most popular type. This is mostly because Ni-rich NMC and NCA chemistries have a high specific energy (Table 3). However, their cycle life is primarily determined by mechanical and thermal design parameters, rather than chemistry alone. LiFePO_4 (LFP) cathodes exhibit excellent intrinsic structural stability and thermal robustness; however, well-engineered NMC cells featuring optimized pressure distribution, multi-tab or tabless current collection, and surface-stabilized electrodes have demonstrated comparable or even superior durability. Thus, the frequently reported longevity advantage of LFP in the literature primarily reflects its resilience under less-optimized cell configurations rather than an inherent electrochemical superiority over NMC-based systems.

Prismatic cells offer enhanced volumetric packaging and CTP utilization, characterized by reduced interconnects, resulting in lower resistance and cost [152,216]. Their broad,

flat faces facilitate uniform and efficient cooling, while rigid can ensure effective control of stack pressure and swelling [217]. Additionally, flexible tab and size options simplify structural integration and servicing [218]. The established LFP supply chain contributes to the development of denser, cooler, less complicated, and more robust packs. It is widely used in EVs, electric bicycles, energy storage, ships, and drones, and has been adopted in various large-scale designs, the latest of which are blade cells manufactured by BYD [199]. The latter led the scope of car electrification to a different path, shifting from the cell to the model and then to the chassis; currently, the cell is used directly in the chassis [219]. Thanks to this design, the space has achieved an estimated 20% improvement in energy efficiency and structural integration in electric vehicles (EVs) compared to previous designs [220]. All the technical specifications of various LFP prismatic cells are shown in Table 5.

The table above presents a comparative analysis of five unique LFP-based prismatic cells, including the blade cell. These cells are designed to meet specific performance standards while balancing trade-offs in energy density, lifespan, power capacity, and intended use. The product categories illustrate the versatility of LFP chemistry in meeting diverse industrial and automotive requirements. The characteristics encompass elevated energy density, extended service life, substantial power, and significant energy at the pack level. The high-energy-density (228 Ah) and long-service-life (228 Ah) cells <commercial names> have comparable dimensions and weight (~4.2 kg), yet their performance characteristics reveal slight variations. The high-energy-density version offers 178 Wh kg^{-1} , focusing on optimizing storage capacity per unit mass, making it ideal for long-range electric vehicles where extending runtime is crucial. The long-service-life variant, while slightly reducing energy density to 176 Wh kg^{-1} , achieves an impressive 15,000-cycle lifespan. Recent improvements in polymer gel electrolytes (GPEs) generated by quasi-solid-state systems, such as $\text{Pyr}_{13}\text{FSI}/\text{LiFSI}$ in PVDF-HFP, have contributed to notable enhancements in electrochemical performance, which is estimated at 80% retention of capacity after 2000 cycles at a current of 1C, marking a significant leap compared to the typical 500–1000 cycle range of standard LFP cells [223]. These improvements reduce polymer crystallization, minimize leakage and swelling, and facilitate the creation of stable solid-electrolyte interphases (SEI). In addition, they minimize impedance growth, substantially prolong cycle life, enhance the stability of the electrode interface, and increase ionic conductivity in the electrolyte ($\sim 3.3 \text{ mS cm}^{-1}$), thereby incorporating the natural mechanical properties of solid materials [224]. The high-powered 119 Ah cell (2.37 kg) is engineered for fast-charge applications, such as BEVs and PHEVs, boasting an estimated energy density of 161 Wh kg^{-1} and the capacity to provide 2 C discharge at -10°C . It also achieves an 80% fast charge in merely 15 min, ensuring dependable performance for flexible driving cycles. The 28 Ah High Power cell, despite its smaller size (0.73 kg), enables even higher rate charging at 6 C/10 C, achieving an energy density of 123 Wh kg^{-1} . It is designed explicitly for HEVs, PHEVs, and power tools, where dimensions and power response take precedence over sheer capacity. A unique methodology is evident in the Blade cell (202 Ah), tailored for enhanced energy performance at the pack level. Instead of focusing solely on improving the gravimetric energy density of individual cells (reported at 166 Wh kg^{-1}) [224], it uses CTP (cell-to-pack) integration, eliminating the need for conventional modules (shown in Figure 9) [225,226].

Table 5. Technical specifications of various LFP prismatic cells [221,222].

Parameter	 228Ah Cell	 228Ah Cell	 119Ah Cell	 28Ah Cell	 135Ah Cell
Product Type	High Energy density	Long Service Life	High Power	High Power	High energy at the pack-level
Manufacturer's Name	CATL	CATL	CATL	CATL	BYD
Chemistry	LFP	LFP	LFP	LFP	LFP
Dimensions (mm)	53.7 × 173.9 × 204.6	53.7 × 173.9 × 204.6	33.2 × 200.3 × 169.6	26 × 148 × 95	965 × 90 × 13.5
Weight (kg)	4.12	4.2	2.37	0.73	2.7 ± 0.3
Energy Density (Wh kg ⁻¹)	178	176	161	123	160
Cycle Life (25 °C, 100% DOD)	4000	15,000	6000	8000	3000
Operating Temperature (°C)	−35° to +65°	−35° to +65°	−35° to +65°	−35° to +65°	−30° to +60°
Application	Long-range EVs	ESS, Solar backup	BEV, PHEV	HEV, PHEV, Power Tools	BEV
Key Features	- High energy density - cost-effective	- Bionic electrolyte - zero fading after 1000 cycles	- 2 C discharge at −10 °C - fast charge 80% in 15 min	- 6 C/10 C fast charging, flexible vehicle integration	- Cells are integrated directly into the pack without modules (higher density) -Withstands crushing, bending, piercing, and heating without failure

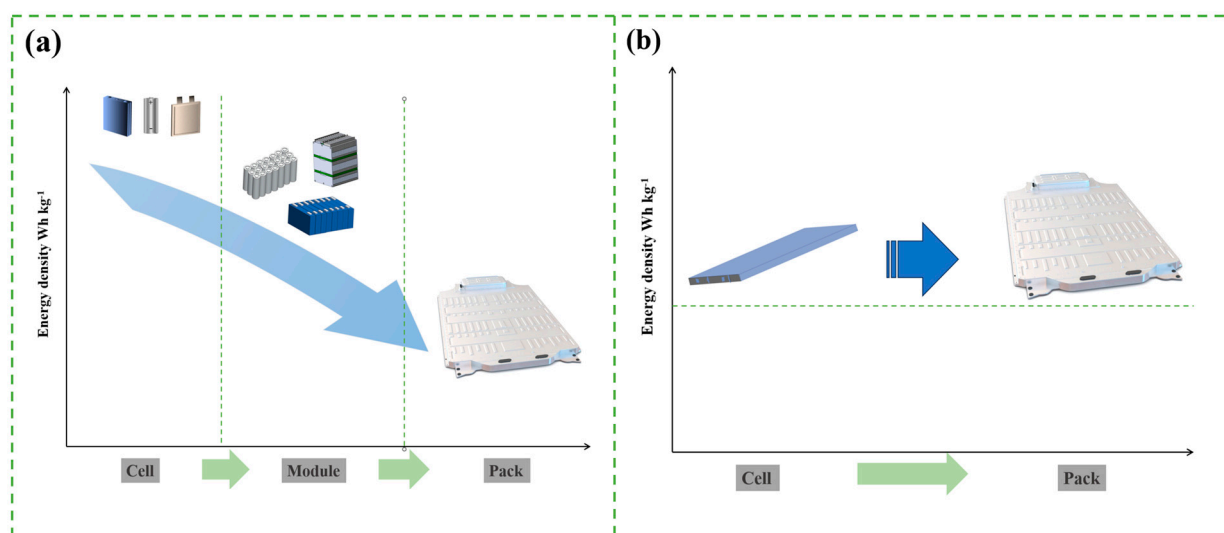


Figure 9. Conventional (a) cell-module-pack vs. (b) blade-style cell-to-pack (CTP): effect on pack-level gravimetric energy density.

Long, thin blade-style prismatic cells serve as rigid, pack-spanning structural elements with large flat cooling surfaces and side terminals [227]. This design enables direct bolting into the pack, providing uniform compression, reducing interconnects, and thereby enhancing energy density at the system level, lowering costs, and improving thermal consistency, facilitating proper cell-to-pack integration. In contrast, many smaller prismatic cells require modules for handling, busbars, and load or cooling management, which undermines the cell-to-pack approach [217,228,229]. These cells are designed to withstand crushing, piercing, and warming without failure, making them particularly suitable for BEVs that require structural batteries and improved security [219,230]. While all products employ LFP chemistry, their design priorities differ significantly: energy cells aim to optimize Wh kg^{-1} for range; long-life cells focus on maximizing cycle count for stationary storage; power cells emphasize current management and thermal resilience; and CTP-integrated cells work to improve pack-level performance and mechanical durability. The tailored strategies demonstrate the exactness with which prismatic LFP cells can be engineered to meet the needs for different markets, from utility-scale storage to cutting-edge electric vehicles [215,231].

Structural optimization involves refining the physical and geometrical configuration of cell components, including electrode architecture, current-collector layout, tab placement, separator thickness, and overall cell format (cylindrical, prismatic [including blade], or pouch), to simultaneously enhance thermal performance and energy density. Optimized cell geometry and current pathways (e.g., tabless or multi-tab designs) minimize localized Joule heating and improve temperature uniformity, thereby reducing degradation and enabling stable operation at higher C-rates. In large-format cells such as Blade or 4680, the use of thinner foils, increased surface-area-to-volume ratios, and integrated cooling channels further promotes efficient heat dissipation and thermal homogeneity [218,232–234].

At the electrochemical level, a uniform coating thickness, controlled porosity, and shorter transport distances lower internal resistance and, consequently, decrease heat generation ($Q = I^2 \cdot R$) [96,161,235]. Structural refinement also enhances the packing efficiency of active materials, thereby reducing inactive mass (including current collectors, casing, and separators) and improving both gravimetric and volumetric energy density [151,160,198]. Moreover, an optimized mechanical design mitigates electrode stress, cracking, and gas evolution, thereby maintaining electrical contact and extending cycle life [164,204,236]. The integration of cooling plates or thermal interface materials at the module or pack level

enhances heat removal without compromising overall energy density, achieving a balanced relationship between safety, performance, and compactness [217,237–239].

Many electric vehicle manufacturers, including BYD, BMW, and Volkswagen, opt for the prismatic battery design due to its higher power density, which results from its compact packaging and ability to withstand significant mechanical stress from its casing [61]. However, a prismatic battery cell can experience considerable stress at the corners during bending due to its packaging method [208]. The thermal management of the EV battery pack, including prismatic cells, is more complex than that of cylindrical and pouch cells [240]. This complexity arises from the lower surface-to-volume ratio and anisotropic thermal pathways, which result in significant internal temperature gradients [217]. These factors require dual-sided or patterned cold plates with precisely controlled contact resistances and stack compression [232,241–243]. Additionally, their generally elevated per-cell capacity (resulting in increased heat generation per cell and heightened propagation risks) and strict ΔT constraints to prevent accelerated aging render pack-level thermal management intricate more [244]. Air and liquid cooling methods have shown significant improvements in thermal regulation and energy efficiency [217]. The hybrid battery thermal management system (BTMS) with liquid cooling and phase change material (PCM) systems has reduced the temperature by 30% and improved temperature uniformity by 13.92% [237]. Based on this data, CATL launched the Qilin battery in 2023 with a record-breaking volume utilization efficiency of 72% and an energy density of up to 255 Wh kg^{−1} for NMC and 160 Wh kg^{−1} for LFP [245]. The Qilin (CTP 3.0) battery utilizes a multi-functional sandwich structure with an elastic interlayer, replacing conventional liquid-cooling plates and thermal pads. This design integrates micron-scale bridges to accommodate internal cell deformation, thereby improving mechanical integrity and reliability throughout the battery's lifespan. Based on advanced heat transfer principles, the architecture enhances thermal management by quadrupling the effective heat dissipation area compared to bottom-cooled systems. The resulting broad-surface cooling technology shortens thermal regulation time by approximately 50%, enabling a 5-min hot start and 10-min rapid charging (from 10% to 80% state of charge) [246].

Recent investigations into prismatic lithium-ion cells with NMC cathodes, using non-destructive X-ray computed tomography, have revealed that structural degradation mechanisms, such as electrode breakdown and electrolyte redistribution, play a crucial role in capacity fade [203]. Hence, its use is limited compared to LFP cells in EVs and ESS. In contrast to that, recent research on NMC-based prismatic lithium-ion cells suggests that optimized mechanical pre-compression effectively reduces direct current internal resistance (DCIR), thereby decreasing Joule heating ($Q = I^2 \cdot R \cdot t$, where Q = heat in joules (J); I = current in amperes (A); R = the resistance measured in ohms (Ω); t = the time duration of the current flow calculated in seconds), and enhancing electro-chemo-mechanical interactions within the cell structure [247,248]. This enhancement results in notable increases in cycle life and safety. Focused studies on calendar-aged prismatic NMC cells have shown that implementing controlled external mechanical constraints can significantly reduce aging-related degradation and performance decline during repeated cycling [249]. This highlights the essential importance of mechanical integrity in prismatic lithium-ion batteries, indicating that applying structural compression techniques offers a practical method to enhance their operational lifespan, thermal stability, and overall electrochemical performance.

LFP cells have demonstrated superior thermal and chemical stability, enabling the development of larger designs at lower cost [182,250,251]. EVE introduced its battery LF560K (352 × 207 × 72 mm; 3.2 V) in the second quarter of 2024, with a nominal Capacity

of 628 Ah [252,253]. This opens horizons and visions for developing larger, safer, and more widely used cell designs.

3.3. Pouch Cells Format

The advent of the pouch cell format in 1995 represented a vital turning point in the design of lithium-ion batteries [254]. Moving away from traditional rigid metallic cylindrical or prismatic designs, the pouch cell features a flexible, laminated polymer-aluminum foil enclosure, with conductive foil tabs directly welded to the electrodes and heat-sealed to the pouch [255]. This method enables efficient routing of the positive and negative terminals to the exterior (as shown in Figure 10).

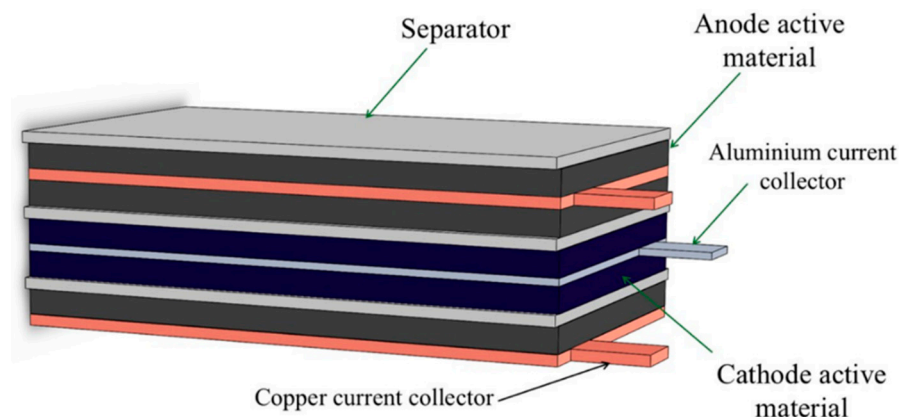


Figure 10. Schematic representation of pouch cell layers [256].

This innovative design achieves an impressive packaging efficiency of 90~95%, designating it as one of the most space- and weight-efficient formats currently available in the industry [257]. The absence of a metal housing results in a significant reduction in overall cell mass, which may be advantageous in weight-sensitive applications such as electric vehicles, airplanes, and portable electronics [258]. Additionally, the engineering ease of the pouch cell offers enhanced design flexibility, enabling fabrication in various sizes and shapes tailored to specific application requirements. Nonetheless, this adaptability results in a compromise regarding structural integrity [259]. Pouch cells, lacking a rigid casing, are susceptible to swelling and require external support mechanisms or compression systems within battery modules to maintain operational safety and extend their longevity [260]. While the pouch format offers several benefits, it is notably affected by environmental conditions; prolonged exposure to elevated humidity or high temperatures can accelerate degradation, potentially leading to electrolyte breakdown, delamination, or gas production [261–264]. Consequently, effective thermal management and hermetic sealing are essential factors in the implementation of pouch cells [265]. Studies conducted by Leonard et al. (2023) have shown that applying and maintaining uniform pressure on the stack reduces swelling, improves interlayer contact, and prolongs the life of the cyst cells [266]. It is also necessary to adopt suitable thermal cooling for the package and ensure sufficient contact between the cold plate and the heat distributor on large surfaces to reduce $T_{\max}$ and ΔT , as heat accelerates unwanted reactions [267].

Pouch format with lithium Cobalt Oxide (LCO) continues to be the favored cathode chemistry in iPhones and various compact consumer electronics, attributed to its remarkably high energy density of approximately 248 Wh kg^{-1} (around 740 Wh L^{-1}) utilizing graphite as the negative electrode, stable voltage profile around 3.7 V [17,132,135], lightweight and compact structure, and a mature, well-optimized manufacturing process [268,269]. These characteristics facilitate extended battery life and efficient use of space

within smartphones' limited form factor. Meanwhile, its known drawbacks, such as poor temperature stability, shorter cycle life of about 500–1000 cycles [270,271], reduced power capability, and the high cost of cobalt—are far less critical in such low-power, tightly controlled environments than they are in highly demanding applications like electric vehicles or grid-storage systems.

In current pouch cell applications, Nickel-Manganese-Cobalt (NMC) chemistry is typically preferred over Lithium Cobalt Oxide (LCO) due to its superior properties [272]. NMC exhibits a commendable energy density of approximately 230–280 Wh kg^{−1}. It boasts an extended cycle life, with capabilities of 1000 to over 2000 cycles [271,273]. Additionally, it demonstrates superior thermal and chemical stability while containing lower cobalt content than LCO, contributing to cost savings and environmental benefits. NMC could potentially identify applications in various other forms of electric vehicles and energy storage solutions.

In contrast, small pouch cells using LCO technology in mobile phones offer limited benefits and thus limited applications. In contrast, large pouch cells employing NMC technology are prevalent in the automotive electrification sector [268]. The Audi E-tron is highlighted for its use of the LG Chem E66A (350 × 104 × 11.7 mm; 897 g) (shown in Figure 11a) [274]. Its flexible shape facilitates the development of 36 models (shown in Figure 11b) and pack designs tailored to the vehicle's specifications (396 V; 240 Ah). Additionally, it is equipped with a cooling system (an integrated liquid-cooling plate under each module) to mitigate the risk of thermal runaway in NMC cells. Audi utilizes protective aluminum enclosures and crossmembers to shield the pack from side or underbody impacts [275]. Cells present 55% of the weight of the battery packs [276].

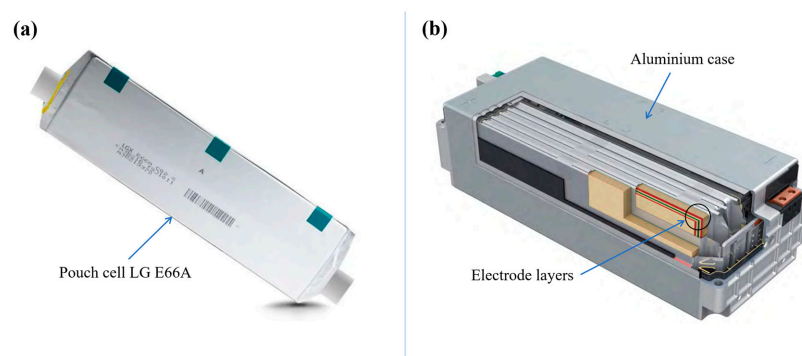


Figure 11. (a) Battery module Audi E-tron 2019 (b) battery pack Audi E-tron 2019, reproduced with permission from [275,277].

On the other hand, LFP technologies exhibit stability at elevated temperatures and do not necessitate the same safety protocols as NMC to avert overheating. This prompted LG to contemplate its application in pouch cells for energy storage systems and cylindrical batteries for electric vehicles in collaboration with General Motors via Ultium Cells LLC, to manufacture 27 GWh of cylindrical cells by 2025 and 16 GWh of pouch cells by 2026 [278,279].

4. Challenges in Lithium-Ion Cells

4.1. Energy Density

Energy density is the amount of energy per unit mass or volume. The assessed value is calculated by multiplying the operation rating of the voltage (V) by the rating capacity (Q) and then dividing the result by the sum of the mass or the entire volume, as well as the practical energy density, which deviates significantly from the theoretical energy density [280]. NMC, NCA, and LCO offer substantially higher energy density

(200–300 Wh kg^{−1}) [61,281,282]. In contrast, LiFePO₄ exhibits a specific energy density of only (160 Wh kg^{−1}) [225], but stands out in terms of safety and longevity [283], which is essential in high-energy applications. Studies are being conducted to dope with additional materials to increase the voltage (4.0–4.1 V), and energy density, such as Mn-rich (60–80% Mn), which is boost to initial gravimetric energy density over LFP with 18%, however it eliminate after 100 cycle, in addition, blend LMFP with NMC811, These methods have led to significant enhancements in the electrochemical properties of LMFP [284].

Coatings such as Atomic Layer Deposition (ALD) and Chemical Vapor Deposition (CVD) improve the ionic conductivity at the cathode surface-electrolyte interface [285–288]. It should be thin, uniform, mechanically rigid, and stable over charge–discharge cycles to prevent cracks and mechanical stress, thereby sustaining battery performance [289]. On the other hand, blending silicon with graphite in lithium-ion battery anodes significantly enhances energy density by leveraging silicon's exceptional capacity (~3579 mAh g^{−1}) while mitigating its challenges, such as considerable volume fluctuations, low conductivity, and an unstable solid electrolyte interphase, due to the stability provided by graphite [290,291]. This enables high-capacity, long-life cells with energy densities that surpass those of conventional graphite systems. Unfortunately, the significant 300% volume expansion of silicon occurs during lithiation and delithiation, resulting in particle pulverization, loss of electrical contact, and the formation of an unstable solid-electrolyte interface (SEI) [292,293]. Various strategies exist for achieving cyclic stability under high areal mass loading. Key components of this study include the design of independent electrodes, the use of polymeric binders, and the adoption of porous substances with high compressive density [294].

Currently, leading electric vehicle manufacturers have employed the Si/graphite anode (10% Si) in 21700 cells, achieving a specific energy of 269 Wh kg^{−1} [292]. The 4680 cells are expected to achieve the same results with next-generation high-energy cathode materials (such as NMC), and silicon-enhanced (10–20%) graphite anodes may achieve 300 Wh kg^{−1} and 800–850 Wh L^{−1} [295]. Consequently, advancing Si/graphite anodes presents a viable approach to achieving commercial applications for Si-based anode materials. Nonetheless, the energy density falls short of the anticipated levels required to advance a more economical Si/graphite anode.

Figure 12 illustrates the historical evolution of gravimetric energy density in individual lithium-ion battery cells (cylindrical, pouch, and prismatic). The following are the specifications of LIB cells from the OEM datasheets (LG Chem Ltd., BYD, Tesla, Samsung SDI, Panasonic, CATL, and others). Thus, the gravimetric energy density curve promises future surprises amid the intense competition from the world's largest companies in the battery field.

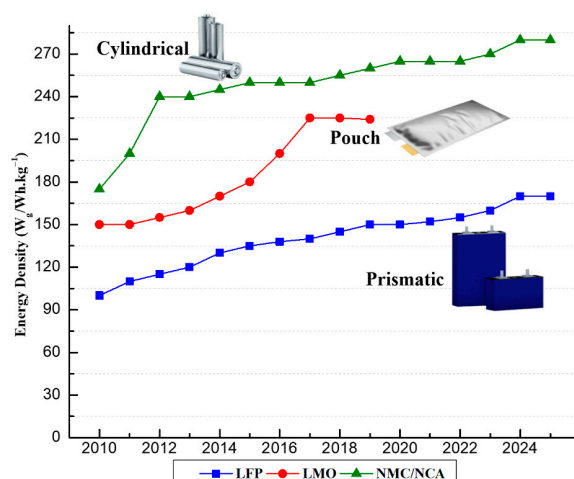


Figure 12. Energy density in different cell types. Data reproduced with permission from [12,200].

4.2. Cost

The need for electricity has driven major companies worldwide to develop technological advances that have helped decrease the price of batteries by 99%, from a high of \$7500/kWh in 1991 to a low 50~70\$ per kWh in 15 August 2024 (as shown in Figure 13a–c) [296–298]; this is due to the decline in prices of basic materials in manufacturing, such as lithium and graphite, and cathode materials [28].

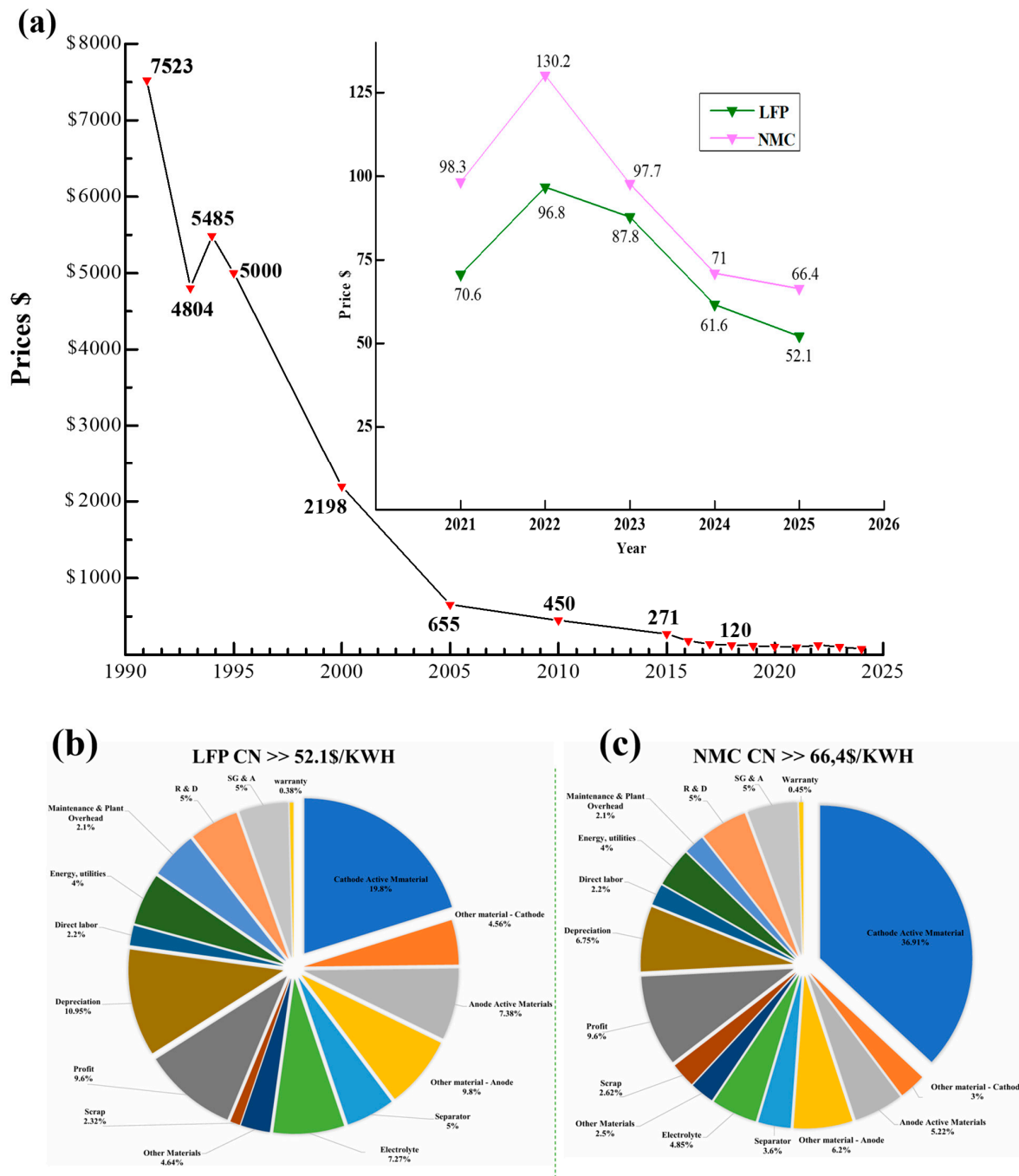


Figure 13. (a) Price of lithium-ion cells (\$)/kWh, (b) Price of LFP/C in China (\$)/kWh, (c) Price of NMC in China (\$)/kWh.

The high cost of lithium-ion batteries substantially impedes their widespread adoption. The price is influenced by various factors, including materials, production methods, and supply chain dynamics [299–302]. The costs associated with these commodities are

significant, and they are further complicated by political and ethical challenges, particularly regarding the extensive cobalt extraction activities in the Democratic Republic of Congo [303,304], and lithium extraction in areas such as South America, Australia, and China [305]. High-energy cathodes, such as NMC and NCA, typically cost more than iron-based alternatives like LFP, despite offering higher energy density. The manufacturing process is energy-intensive and requires significant capital investment, particularly in the production of electrodes, which collectively account for about 35–45% of the overall battery manufacturing cost [306–308].

The jelly-roll design offers significant benefits for manufacturing by facilitating rapid, automated production [147]. The spiral structure effectively withstands vibration and compression, making it advantageous for electric vehicles and power tools [235]. It guarantees uniform current distribution and radial thermal dissipation, resulting in a standardized, cost-efficient structure with reasonable volumetric efficiency that upholds in-line cell reliability and quality in electric vehicle and energy storage applications [309]. Unlike cylindrical cells, which use standardized metal cans (such as 18650 or 21700), prismatic cells require custom aluminum casings, either welded or folded, which increase material and tooling costs. In addition, prismatic cells use stacked electrodes, whether in a Z-fold or flat-stack configuration, which necessitates careful alignment and layering [310]. This method results in longer assembly times and greater complexity than the efficient jelly-roll winding technique used for cylindrical cells.

The Blade cell, although categorized as a prismatic-format battery, has notably lower manufacturing costs per kilowatt-hour than traditional prismatic cells. It is elongated, slender, high-aspect-ratio prisms featuring case “support areas” and side/end terminals that extend directly between pack rails, functioning as structural components [311]. This configuration enables busbars and a single continuous cold plate to traverse the cell rows, facilitating genuine cell-to-pack assembly by eliminating module packaging and hardware, thereby enhancing volume utilization, streamlining interconnects and compression, and reducing part count [219]. In the automotive sector, cylindrical cells necessitate the assembling of hundreds to thousands of small-format units per pack, requiring meticulous individual alignment, spot welding, and numerous busbar connections, along with additional processes such as cell holders, fusing, and routing, which collectively render the pack assembly process more labor- and equipment-intensive [151,312,313]. Conversely, Blade cells, being large-format and structurally uncomplicated, facilitate a streamlined stack-and-connect arrangement with fewer welds and components, supporting direct Cell-to-Pack (CTP) integration. This significantly reduces assembly complexity, enhances scalability, and lowers manufacturing costs in the production of electric vehicle batteries. CATL and BYD demonstrated their leadership in reducing battery prices by implementing LFP technology, which is considered the most cost-effective option available [306]. The pouch format incurs additional packaging and heat-control costs, highlighting the rising unit cost. It is essential to emphasize that achieving cost savings in battery design requires a careful balance between manufacturing efficiency, thermal endurance, and volumetric constraints, all of which are influenced by the selected cell architecture. The specific requirements of the application will determine whether to use prismatic, pouch, or cylindrical cells. Each design presents unique advantages, and producers meticulously evaluate cost, flexibility, and spatial constraints to select the most suitable cell type for a specific application.

The primary challenges in producing reliable and affordable battery cells include fluctuating manufacturing costs, especially for electric vehicles, due to the market’s relative newness and the scarcity of experienced workers. Only in the last five years has mass production begun, suggesting a limited understanding of electric vehicle applications. As the market grows rapidly, the gradual accumulation of industry expertise is driving cost

reductions through enhanced production processes. The ongoing changes in demand and supply, coupled with a lack of equilibrium, result in significant price volatility. Factors such as the potential for a few companies to dominate the market, limited access to information, and advancements in technology or the discovery of new sources of raw materials create a complex system that affects the cost and pricing of batteries worldwide. The application of innovative cell chemistries is transforming the demand for existing materials, and as a result, their associated costs are changing. In current investigations, the costs associated with battery cells are heavily influenced by material prices, which are significantly affected by the volume of purchase, a factor that also fluctuates.

4.3. Safety

The growing adoption of electric vehicles, advancements in mobile technology and energy storage, and innovations in aerospace that rely on lithium-ion batteries have made safety a critical focus in their research and production processes [314–316]. Increasing energy density improves performance; however, it also increases the risks of thermal instability, mechanical stress, and electrical failure [317]. Lithium-ion cells can fail in different ways that might lead to a fire or explosion, often due to overcharging or over-discharging, which can damage the electrodes and trigger harmful reactions [233,318]. The separator may fail, or lithium dendrites could form, potentially leading to shorts within the cell. Additionally, mechanical damage can affect electrodes, leading to gas emissions.

A common challenge with cylindrical cells is their lower volumetric efficiency at the package level, because round cells leave voids in the modules and packages. In classic cells, high cell count results in thousands interconnections, heightening the risk of resistive failures; Gas accumulation during operation induces stress on vents and, if improperly directed, may lead to a jet flame; Manufacturing defects such as burrs, contaminants, and spacer misalignment can result in significant internal shorting; Aging leads to increased gas and impedance, causing elevated heat under load, and the low volumetric utilization at the package level may restrict the space available for robust thermal barriers unless meticulously engineered [151]. Therefore, larger cells with a tabless design, such as a 4680 cell, were suggested to diminish the number of connections and further decrease resistance.

Prismatic EV modules experience rapid charging heat stress due to conventional side and bottom plates, making it more challenging to maintain cell temperature limits. The incorporation of a top plate serves as a thermal bridge, facilitating temperature homogenization and reducing cool-down time. However, busbars and terminals may develop hot spots due to their lower thermal mass, leading to slower cooling and larger temperature differences without dual-sided cooling [142]. Ideally, the Battery Thermal Management System (BTMS) should maintain cell temperatures between 20 and 50 °C with a temperature difference (ΔT) of ≤ 5 °C [237]. While phase change material (PCM) layers enhance uniformity, their low conductivity and potential for leakage or melting under extreme loads necessitate hybrid designs (liquid + PCM) to ensure that the maximum heat and temperature differentials remain within specifications [217,238]. Blade cells position the current take-off on both sides, provided that the tongues are distributed on both sides of the bus bars and the current path to each electrode is short and uniform [227]. This reduces heating ($I^2 \cdot R$), lowers the terminal temperatures, reduces voltage drop, and thus reduces the risk of thermal runaway during fast charging.

Cells' form factor is closely related to the nature of cathode chemistry. LFP cells can withstand voltages of around 4.2 V with minimal electrochemical degradation, whereas NMC/NCA/LCO cells exhibit oxygen evolution and cathode failure at 4.3 V [319]. The improper use of electrolytes or exposure to elevated temperatures may result in the emission of flammable gases, which can adversely affect the electrolytic characteristics of the

solution [320]. The most hazardous type of thermal runaway is characterized by the initiation of an exothermic reaction that progresses autonomously and becomes irreversible once it commences.

LFP exhibits greater thermal stability than nickel-rich compounds, such as NMC, NCA, and LCO [321]. The olivine structure exhibits robust P-O bonds that inhibit oxygen release, even at high temperatures. LFP starts to break down at around 270–300 °C without letting out oxygen, which helps prevent overheating problems [322]. LFP cathodes, used by BYD, CATL, and Ford, exhibit lower energy density than NMC [251]. The extended lifespan, reduced cost, and improved thermal reliability of LFP cathodes, particularly with advanced designs like Blade, represent significant advantages. These benefits include excellent thermal safety, as demonstrated by tests where nails were driven through them without catching fire, excellent space efficiency in designs that do not require separate modules, and a long lifespan of over 3000 charge and discharge cycles [215,323,324]. All these factors make LFP cathodes the top choice for large-scale, safe, and affordable energy storage in popular electric vehicles and stationary devices.

NMC and NCA consist of layered transition-metal oxides that exhibit significant oxygen release during decomposition, often triggering thermal runaway between 210 and 240 °C [325–327]. The risk is heightened in nickel-rich NMCs, such as NMC811 and NCA, due to their higher capacity and lower thermal decomposition temperatures. LCO, despite its historical significance, exhibits the lowest thermal stability, with exothermic decomposition and oxygen release initiating at approximately 190–230 °C [328], thereby increasing its susceptibility to fire or explosion under abusive conditions.

Recent lithium-ion battery cells feature safety devices to reduce cell failure. Cylindrical cells benefit from Current-Interrupt Device (CID) and Positive-Temperature-Coefficient (PTC) fuses; when current or temperature levels exceed or fall below the specified criteria, the circuit shuts off [233]. Multilayer separators, usually ceramic, may shut off the device to prevent internal short circuits at high temperatures [329]. Additionally, electrolyte mixtures contain certain substances that reduce gas production and enhance the stability of the solid-electrolyte interphase (SEI). A key concern is the use of flammable organic electrolytes, which can catch fire. This has led to research on flame-retardant materials and non-flammable solvents such as FT46 [330,331], and solid-state electrolytes [332].

Design plays a crucial role in determining battery longevity, and research is underway to integrate chemistry and design to enhance battery performance. LG Energy Solution has proposed new battery designs called “AZ stacking”. It relies on Z-stacking technology with thermal compression (as shown in Figure 14). Its advantages include improved adhesion between electrodes and separators, reduced structural distortion, and enhanced safety, primarily by reducing overhang issues. It also improves space utilization and reduces production time compared to conventional cells [333].

The binder plays a critical role, primarily maintaining the structural integrity of electrode material particles (such as LiFePO_4) with conductive materials (such as hard carbon, PVDF, PTFE, KS6) [334,335]. Furthermore, binders play an essential role in improving the stability of natural battery systems by protecting electrodes from humidity, temperature fluctuations, and other external factors [336,337]. It is necessary to develop binders that exhibit exceptional mechanical strength, remarkable bonding characteristics, electrochemical stability, and non-toxicity [338–340].

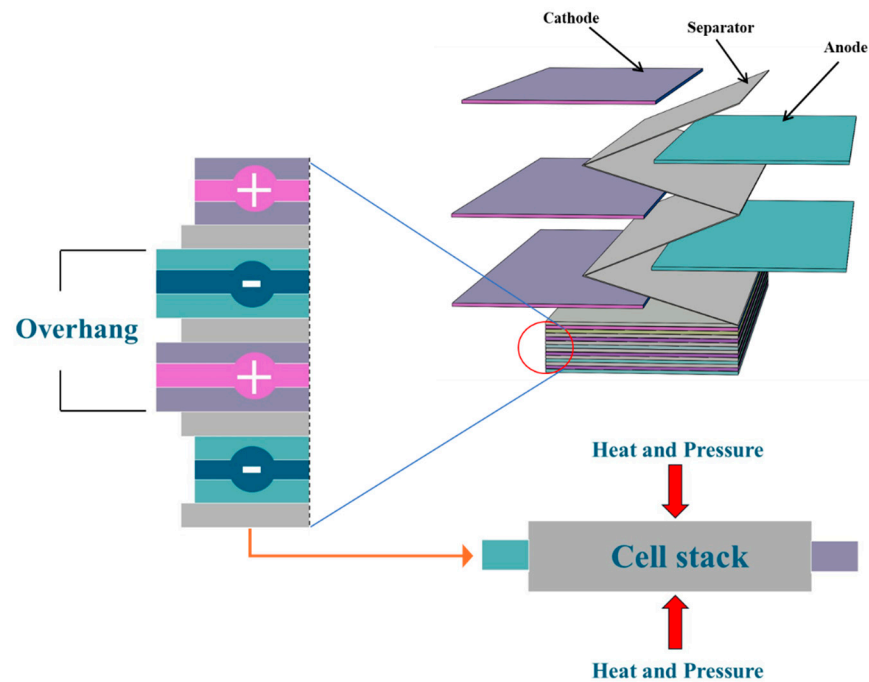


Figure 14. LG Energy Solution's Advanced Z-stacking (AZS) [333].

4.4. Battery Management System (BMS)

Lithium-ion cells are sensitive to factors such as overcharging and over-discharging [341,342]. Therefore, the battery management system has been adopted to enhance its performance and ensure safety in various applications, including electric vehicles and energy storage systems [241,242,343]. It serves as an intelligent control unit that monitors and manages these parameters to ensure optimal performance.

The BMS topology affects cable length and quantity, sensor granularity, balancing, and fault-isolation strategy, thereby influencing the practicality of cell form factor-centralized Battery Management Systems (BMS) [344]. Extensive lead lengths exhibit poor scalability and increasing harness risk with elevated cell counts [345]. In contrast, modular, distributed, or decentralized BMS positioned proximally to cells minimize lead lengths and enhance measurement reliability, facilitating packs composed of numerous small cylindrical cells [346]. Conversely, packs constructed from fewer, larger prismatic or pouch cells, including cell-to-pack (CTP) configurations, decrease channel requirements and promote decentralized diagnostics; thus, original equipment manufacturer (OEM) system topologies differ based on cell format [347].

Significant challenges in the design of modern battery management systems encompass enhancing real-time estimation of states (SoC/SoH), efficiently addressing cell imbalance in extensive configurations, ensuring effective thermal management to support rapid charging and fluctuating loads, preventing the propagation of cell-level faults across the system, and incorporating innovative and flexible control algorithms that align with embedded hardware limitations [348]. The real-time estimation of charge and state of health in lithium-ion batteries poses significant challenges due to nonlinear degradation and variability across different chemistries [349–352]. However, recent advancements in machine learning techniques, such as LSTM (Long Short-Term Memory), DeepHit, and reinforcement learning, provide enhanced accuracy and adaptability [353,354]. These new features enable fast charging methods that prioritize both battery life and performance.

The increasing number of lithium battery packs complicates maintaining a uniform state of charge (SoC) across cells, potentially leading to imbalances and accelerating their degradation. In contrast, BMS designs are being developed based on BLE, ZigBee, and

Wi-Fi technologies to eliminate traditional wiring [355–358]. The goal is to reduce costs and improve scalability. However, these designs are still in their early stages of research due to safety and data security challenges. The combination of advanced AI/ML models (Artificial Intelligence and Machine Learning) represents a significant step forward in battery management system technology, enabling the calculation of State of Charge (SoC), State of Health (SoH), and Remaining Useful Life (RUL) [359–361]. On the other hand, AI/ML enables thermal control, temperature prediction, dynamic cooling adjustments (e.g., PCM and hybrid cooling systems), and thermal runaway prevention [362]. Innovative charging methods improve performance, enhance safety and battery life, and increase charging efficiency in electric vehicles and large-scale storage systems [363,364].

4.5. Thermal Runaway

The issue of thermal runaway in lithium-ion cells was recognized in the early 1990s, shortly after their commercial introduction. Elevated temperatures from internal short circuits, separator defects, overcharging, external heating, or mechanical damage led to the breakdown of cell components, separator shrinkage, and gas emissions that can occasionally trigger combustion. The severity and probability of thermal runaway vary significantly depending on the cathode chemistry (shown in Table 6), due to differences in structural and thermodynamic properties. Understanding these differences is critical for material selection and safety engineering in lithium battery design.

Table 6. Thermal Runaway Overview in Major LIB Cathodes.

Chemistry	LFP	NMC	LCO	NCA	LMO	Reference
TR Onset/Peak (°C)	270–360	~200–269	150–230	160–190	151–261	[365–369]
O ₂ Evolution from Cathode	✗ None	☑ Yes	☑ Yes	☑ Yes	△ Moderate	[75,370–373]
Exhaust gases	H ₂ , CO, CO ₂ , C ₂ H ₄ , CH ₄	C ₂ H ₄ , C ₂ H ₆ , C ₂ H ₅ F, C ₃ H ₈ , CH ₄	CH ₄ , CO ₂ , CO, C ₂ H ₆ , C ₃ H ₈ , C ₃ H ₆	CO ₂ , H ₂ , CH ₄ , C ₂ H ₄ , CO	CO ₂ , CO, H ₂ , C ₂ H ₄ , C ₃ H ₆ , C ₃ H ₈ , H ₂ O	[374–376]
Gas Generation (Volume)	Low	High	Very High	High	Medium	[236,377–380]
Heat Release (J g ^{−1})	145 > Yamada et al. 250 > Zaghieb et al. 290 > Martha et al.	512.5–971.5 NMC111: 512.5 > 260 °C NMC622: 721.4 > 260 °C NMC811: 904.8 > 260 °C	190–230 °C: ~420 ± 120 230–300 °C: ~1000 ± 250	850 ± 100	350–450	[234,279,280, 381–383]
Failure Mode	Venting only/stable	Fire/explosion possible	Fire/explosion likely	Fire/explosion possible	Mild venting/low fire risk	[323,324,384]
Thermal Stability	Excellent (★★★★★)	Moderate (★★)	Poor (★)	Moderate (★★)	Good (★★★★)	[385–387]
TR Risk Level	Very Low	Medium	Very High	Medium-High	Low-Medium	[385]

After dominating LCO batteries for more than two decades, they have gradually been replaced in many sectors and applications where safety is a top priority. NMC and NCA chemistry offer a balance between high energy density and moderate risk of thermal damage, provided robust safety and control systems are integrated. As for LFP chemistry, it is characterized by exceptional thermal stability, with a thermal runaway onset above 250 °C, minimal oxygen release, and low heat generation [271,288,292], making it suitable for safe applications such as energy storage and entry-level electric vehicles. Several studies support these mechanistic differences, including Zaghieb, K. et al. (2011) [388] and Fan, T.

et al. (2023) [389], which highlight the critical trade-off between energy performance and safety in battery designs.

The thermal runaway behavior in lithium-ion cells is primarily determined by the redox activity and strength of the transition-metal components used in the cathode [390]. Nickel (Ni), frequently present in high-energy cathodes such as NMC and NCA, is pivotal because of the emergence of Ni^{4+} at elevated states of charge; that oxidation state is notably unstable and encourages oxygen to escape from a cathode lattice structure at temperatures of 180 °C, resulting in swift generation of heat and exothermic interactions with the electrolyte [391]. Regarding high-Ni (NMC811) cells, Self-generated heat initiates around 94.5 °C, primarily due to SEI breakdown and short circuits. At 228 °C, thermal runaway is initiated as the decomposition of the cathode, induced by nickel, releases oxygen, which subsequently ignites the electrolyte [369]. Cobalt (Co), present in LCO and in specific NMC/NCA formulations, shifts to Co^{4+} during delithiation, leading to earlier oxygen emission [392]. On the other hand, iron (Fe), present in the olivine-structured LFP, exhibits a notably stable $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox couple [393]. PO_4^{3-} effectively binds lattice oxygen [373]. And thus, LFP exhibits exceptional thermal stability, characterized by minimal heat release [365,394]. Manganese (Mn) typically exists as Mn^{4+} in stable forms and is used in LMO and as a stabilizing element in NMC. However, Mn^{3+} can disproportionate into Mn^{2+} and Mn^{4+} ; consequently, Mn^{2+} disintegrates into the electrolyte, damaging the anode SEI and triggering gas generation along with increased internal resistance [395–401]. While Mn itself does not directly cause oxygen release, it indirectly contributes to thermal instability. Comparative analyses of chemistries (NMC vs. LFP) under controlled abuse scenarios (thermal exposure, nail penetration) demonstrate that LFP exhibits greater thermal stability than NMC [316–318]. The results indicate that NMC cells exhibit faster temperature escalation, a greater propensity for swift thermal runaway, and a higher volume of hazardous or emissive gases.

Several innovative techniques have been employed at the cell level to prevent thermal runaway. This encompasses thermally sensitive safety layers, which are polymer-coated (polythiophene) on current collectors. These layers transition to an insulating state above about 100 °C, thereby halting current flow as the internal temperature rises. This technique has been tested on pouch cells, and the risk of explosion has diminished by 53% during impact testing [402]. This has also been demonstrated by incorporating polymers into the electrodes, which prevent ion transport at high temperatures, effectively isolating the cell internally without any loss in electrochemical performance [403,404]. Additionally, incorporating metal-coated separators or current collectors that increase resistance upon deformation or heating can locally mitigate energy release [324]. Thermoresponsive polymers could likely provide guidance and ideas for designing the next generation of high-security electrostatic discharge devices with intelligent self-protection.

During abuse of cylindrical Li-ion cells, separator softening raises internal pressure that trips the CID and vents a high-velocity jet through the scored top cap, unless venting is impeded, in which case sidewall/cap rupture can occur, a sequence confirmed by operando imaging/cap studies and recent vent mass-flow/pressure measurements used to refine pack gas-management models [405–407]. Prismatic and blade cells use safety valves and burst lines calibrated for a vertically collimated jet, where the type of valve and burst pressure affect the transition to rapid discharge and the jet's characteristics [408]. Extensive testing indicates that vent-path jet fires depend on the initiation site, orientation, and atmospheric pressure, suggesting that precisely calibrated valves enhance burst consistency and enclosure routing [409]. On the other hand, pouch cells (laminates) lacking a rigid vent stack experience progressive swelling, leading to edge or seam rupture and a jet or flame [410].

Blade cells (long prismatic LFP; CTP) attain high packing efficiency but result in extended heat and current pathways [408]. In approximately 280 Ah LFP prism, electrolyte vaporization and axial thermal gradients dictate valve actuation timing and jet persistence [411]. Evidence comparing chemistry and geometry (e.g., LCO > NCM > LMO > LFP nail-test severity) indicates LFP's reduced heat release, although format and test conditions ultimately govern jet and rupture behavior [412]. The following table (Table 7) provides a quick summary of how the thermal runaway profile varies across cell formats and what this means for safety design.

Table 7. Comparison of the effect of thermal runaway in different formats.

Format	Primary Pressure-Relief Path	Jet Directionality	Typical Failure if Relief is Impeded	Notes	Ref.
Cylindrical	CID + top-cap vent	Axial, focused	Sidewall/cap rupture	Rich operando data for timing of CID/vent.	[405,406]
Prismatic	Safety valve/burst line	Vertical, collimated	Lid deformation/wall tear	Valve type & burst pressure steer TR onset/jet	[408]
Pouch	Laminate seam/edge rupture	Diffuse, multi-directional	Edge tear, wide gas dispersion	Edge orientation affects jet/flame evolution	[410]
Blade (Long pris. LFP)	Safety valve (long can)	Vertical jet; length-dependent dynamics	Local deformation, if delayed venting	Axial gradients; LFP chemistry moderate heat	[411,413]

4.6. Fast Charging

The management of lithium plating represents one of the most critical obstacles in the field of fast-charging lithium-ion batteries. This issue occurs when the charging rates exceed the electrode's ability to intercalate Li^+ . The rise in heat generation and electrode overpotential intensifies the degradation of the solid electrolyte interphase (SEI), leading to electrolyte breakdown and a swift capacity decline, heightened safety concerns, and a reduced cycle lifespan [414–416]. Lithium ions can form lithium metal at the anode rather than intercalate into graphite [417]. This process can also lead to uneven ion distribution across electrodes and localized current densities, resulting in irregular aging, diminished efficiency, and elevated risk of internal shorts and thermal runaway, particularly when cells are subject to mechanical compression or high C-rates in high-speed applications. Additionally, the application of high-voltage fast charging imposes significant stress on cathode materials, particularly NMC and NCA. This condition can result in problems, including microcracking, cation mixing, and the dissolution of transition metals, ultimately leading to a failure in ionic conduction [414].

Despite the development of fast charging protocols and strategies, as well as thermally adaptive charging systems that dynamically manage heat to prevent paint damage while enabling charge cycles as short as 15 min [418,419], overcoming the physical limitations of lithium mobility and material stability remains a challenge [420]. Therefore, pioneering research focuses on health-conscious reinforcement learning protocols that balance charging speed and battery life, mitigate side reactions resulting from SoH-dependent voltage limitations, such as those in TD3 [421], develop improved nanomaterials and electrolyte formulations, and suppress dendrite growth under extreme discharge/charge conditions [422].

Fast-charging performance is fundamentally constrained by cell form factor [423], because geometry sets the electrical and thermal path lengths: thus cylindrical jelly-rolls tend to exhibit higher effective in-plane resistance and stronger hot-spotting unless current collection is upgraded (multi-tab or tabless), while winding curvature introduces N/P utilization asymmetry and reaction non-uniformity across the radius; operando/impedance work with segmented tabs directly reveals spatial potential/current-density gradients

governed by tab topology [199,424–426], and since Li plating onset is triggered by local overpotential and temperature rise flattening these gradients via improved current collectors and thermal paths raises the allowable fast-charge C-rate; consistent comparative studies further show larger resistance growth and thermal stress in cylindrical formats under aggressive cycling, reinforcing that architecture-driven mitigation (multi-tab/tabless + better heat spreading) is central to pushing fast-charge limits [427,428]. A substantial body of literature has documented the impact of form factor, engineering, and design mechanisms on fast charging, as outlined in Table 8.

Table 8. Fast Charging vs. Cell Form Factor: Evidence Summary.

Claim	Mechanism/Observation	Design Implication	Ref.
Cylindrical higher effective path resistance unless mitigated.	Longer in-plane current paths in jelly-roll; single-tab causes uneven current lines	Use multi-tab or tabless collectors to reduce I.R and hotspots.	[177,198]
N:P effective area mismatch from curvature	Curved winding changes local pressure/separation → non-uniform reaction utilization	Re-optimize coating and stacking to reduce fast charging and balance utilization more effectively.	[424]
Form factor determines fast-charge limits.	Geometry controls electrical & thermal paths, leading to overpotential & ΔT during charge.	Fast-charge bound by ohmic/thermal constraints; watch Li-plating onset	[429]
Resistance/current-density gradients depend on tab topology	Segmented or operando measurements reveal spatial potential gradients across the tab layout.	Arrange tabs symmetrically, add parallel tabs, and shorten lead lengths.	[234]
Mitigating gradients delays lithium plating.	Lower ohmic drop and flatter temperature field push plating onset to higher C-rates	Combine tab upgrades with thermal spreaders and charge profiles	[430,431]

4.7. Recycling of Various Cell Formats

The recycling process for lithium-ion batteries is influenced by both the electrode chemistry and the cell design. The fundamental recovery processes, including mechanical dismantling, pyrometallurgical smelting, and hydrometallurgical leaching, are predominantly determined by chemistry [432,433]. However, the geometry and structure of the cells play a significant role in affecting the efficiency and cost of recycling operations.

Cylindrical cells, such as 18650, 21700, and 4680, are typically easier to handle in automated recycling lines due to their uniform dimensions and sturdy casings. This design facilitates efficient mechanical shredding and sorting processes [434,435]. Prismatic and Blade cells pose greater challenges due to their rectangular shape, welded tabs, and integrated modules, which necessitate more precise disassembly steps [436]. Pouch cells, on the other hand, use flexible polymer-aluminum laminates and adhesives that complicate material separation and often reduce recovery yield. Emerging research emphasizes “design-for-recycling” approaches, such as modular pack architectures, minimal adhesive use, and labeling of material constituents, to enhance recyclability and reduce end-of-life environmental impacts [437]. These aspects may become increasingly important as large-format cells, such as Blade or 46xx, become dominant in electric-vehicle applications, underscoring the need to align cell design with circular-economy principles.

5. Conclusions

The engineering of lithium-ion batteries has a profound impact on modern life, providing exceptional energy storage performance that powers nearly every aspect of contemporary technology, including smartphones, laptops, electric vehicles (EVs), and renewable energy storage systems. Among the three primary cell formats (cylindrical, prismatic, and

pouch), each offers distinct benefits and compromises, influenced by material chemistry and engineering constraints. Cylindrical cells (e.g., 18650, 21700, 4680) are recognized for their strong mechanical stability and well-established automation, making them widely used in electric vehicle and power tool applications. However, cylindrical cells face limitations in packing efficiency, which restricts their volumetric energy density and complicates space utilization. NMC and NCA chemistries are closely related to cylindrical cell chemistry due to electrochemical advantages and the purpose of improved power and thermal regulation. Conversely, LFP chemistry leverages structural stiffness and near-complete space optimization in prismatic and blade designs to enable secure, cost-effective integration. This minimizes the need for additional support systems and frameworks, enabling a higher energy density per unit volume. The application of LCO cells is limited, primarily in embedded electronics such as mobile phones, due to their high volumetric energy density. Nonetheless, their extensive use is constrained by inadequate thermal stability, elevated cobalt costs, safety hazards, shorter cycle life than NMC cells, and reduced energy density. Their limitations render LCO cells inappropriate for high-power or large-scale applications, including electric vehicles and energy storage systems.

The relationship between cell chemistry and format choice is critical: high-energy NMC/NCA chemistries utilize cylindrical or pouch formats to achieve enhanced energy density and thermal regulation, while LFP chemistries leverage the structural rigidity of prismatic and blade forms for secure and economic integration. Innovative ideas such as CTP (Cell-to-Pack) and advanced blade designs have expanded the boundaries of feasibility, enhancing safety in thermal management and achieving high energy density by eliminating intermediate modules.

Cylindrical cells offer a significant advantage due to their compatibility with automated, high-speed manufacturing processes, making them optimal for mass production at comparatively low cost. Prismatic and pouch cells require more sophisticated equipment and a greater investment in assembly and sealing processes to ensure optimal performance and safety. The choice of the optimal cell design depends on the characteristics of the intended application, necessitating a careful balance among various technical considerations. These include specific and volumetric energy density, efficient thermal management, mechanical robustness, the feasibility of large-scale manufacturing, and the cost of energy generated per kilowatt-hour. These are all essential factors to consider when designing efficient and sustainable battery systems in fields such as electric mobility and energy storage. Looking ahead, LiMnFePO_4 (LMFP) emerges as a highly promising evolution of LFP chemistry, offering higher operating voltage and energy density while preserving the intrinsic safety, long cycle life, and low cost that make LFP attractive. Integrating LMFP into optimized prismatic, blade, or large-format cylindrical configurations could bridge the gap between high-safety, low-cost chemistries and high-energy performance systems. As electric vehicles, storage systems, and electronic devices advance, upcoming innovations in material engineering (such as solid-state electrolytes and high-nickel cathodes), cell geometry (including large-format cylindrical or stacked prismatic designs), and manufacturing scalability will transform optimal design paradigms. A comprehensive grasp of the interactions among format, chemistry, and system integration is crucial for steering the development of advanced, safe, and sustainable lithium-ion batteries.

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