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Review

Cell Architecture Design for Fast-Charging Lithium-Ion Batteries in Electric Vehicles

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Abstract: This paper reviews the growing demand for and importance of fast and ultra-fast charging in lithium-ion batteries (LIBs) for electric vehicles (EVs). Fast charging is critical to improving EV performance and is crucial in reducing range concerns to make EVs more attractive to consumers. We focused on the design aspects of fast- and ultra-fast-charging LIBs at different levels, from internal cell architecture, through cell design, to complete system integration within the vehicle chassis. This paper explores battery internal cell architecture, including how the design of electrodes, electrolytes, and other factors may impact battery performance. Then, we provide a detailed review of different cell format characteristics in cylindrical, prismatic, pouch, and blade shapes. Recent trends, technological advancements in tab design and placement, and shape factors are discussed with a focus on reducing ion transport resistance and enhancing energy density. In addition to cell-level modifications, pack and chassis design must be implemented across aspects such as safety, mechanical integrity, and thermal management. Considering the requirements and challenges of high-power charging systems, we examined how modules, packs, and the vehicle chassis should be adapted to provide fast and ultra-fast charging. In this way, we explored the potential of fast and ultra-fast charging by investigating the required modification of individual cells up to their integration into the EV system through pack and chassis design.

Keywords: lithium-ion batteries; fast and ultra-fast charging; electric vehicles; internal cell architecture; cell design; system integration

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1. Fast- and Ultra-Fast-Charging Batteries

Demand

The global shift towards sustainable energy solutions is one of the factors that has accelerated the development of battery technologies [1]. Electric vehicles (EVs) have emerged as one of the most significant contributors to efforts toward reducing greenhouse gas emissions and increasing energy efficiency [2]. Worldwide EV sales increased by over 14 million units in 2023, which means a 30% increase from 2022, and trends are expected to continue beyond more than 400 million EVs on the road by 2035 [3]. This indicates rapid growth in the acceptance of EVs, especially in China, Europe, and the US. In addition, the cost of lithium-ion batteries (LIBs) in EVs continues to decline, which makes EVs more affordable. With growing affordability and increasing interest in widespread adoption, expanding reliable fast-charging infrastructure is key to making EVs more practical and reducing concerns about running out of charge. LIBs, particularly those with LFP (lithium iron phosphate) [4], NMC (nickel manganese cobalt) [5], and NCA (nickel cobalt aluminum) [6] chemistries, have been designed to support fast charging [7].

Fast charging technology has emerged as a critical focus for the EV industry to address range concerns and reduce charging times. However, it has yet to reach levels comparable to traditional refueling, and thus, it needs extra effort to realize this goal through fast- and ultra-fast-charging approaches. In terms of fast-charging infrastructure, the global distribution is increasing. According to the U.S. Advanced Battery Consortium, EV extreme fast charging achieves 80% of battery capacity within 15 min or less [8]. Similarly, the US Department of Energy and the European Technology and Innovation Platform have outlined fast-charging targets of sub-20 min charging by 2030 [9,10]. In 2023, there are over 2.7 million installations of public charging points worldwide, a third of which are fast charging stations. In nearly 60% of these, China leads, followed by Europe and the United States, which are improving their positioning in installing ultra-fast charging stations capable of charging in 10–15 min as a reasonable goal [11,12].

The demand for fast charging requires increasing the power density of battery cells (mainly at the expense of energy density), resulting in trade-offs between range and charging speed [13]. EV charging levels are classified by power supply and charging speed, as shown in Table 1. Level 1 charging uses 120 V household outlets. It has slow rates to charge, which is ideal for overnight home use. Level 2 charging uses 240 V power and significantly reduces charging times to just a few hours, which would be suitable for daily home or public charging. Level 3 charging, also known as DC fast charging, uses a much higher voltage, often 350 V or above, and is designed for rapid charging, which can deliver substantial power quickly. For instance, the charging performance of the Tesla Model 3 and Nissan Leaf across three different charging levels are illustrated in Table 1, showing how higher voltage dramatically reduces charging times and supports fast and ultra-fast charging. In another way, fast charging can be classified as charging rates above 50 kW, which can go up to 350 kW or higher with today's advanced technology and the introduction of ultra-fast charging [14–16]. Fast chargers provide a maximum charging speed up until about 80% SOC, after which the charging rate slows down due to limitations in the battery's internal resistance to prevent overheating or degradation [10]. For instance, a 60 kWh battery charged at 11 kW would take approximately 4.5 h to reach an 80% state of charge (SOC). Fast charging at 150 kW (DC) reduces the time to 30–40 min for the same 60 kWh battery to replenish to an 80% SOC. While fast charging can significantly reduce charging time from several hours to just 30–40 min, it also introduces challenges regarding battery aging [17]. Comparing fast charging at 50 kW (~2C rate) to standard 3.3 kW AC Level 2 charging shows that while individual cells may experience minimal degradation, battery packs can experience higher capacity fade and, thus, complex aging at the pack level. Techniques like delayed fast charging have minimized degradation more effectively than continuous fast or standard AC charging [17].

Table 1. Overview of charging levels and their influence on fast charging performance.

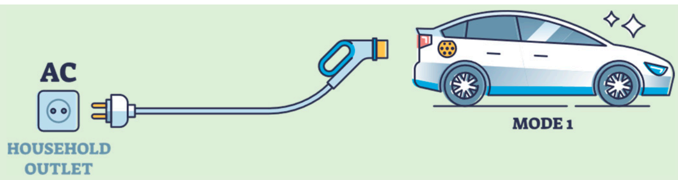
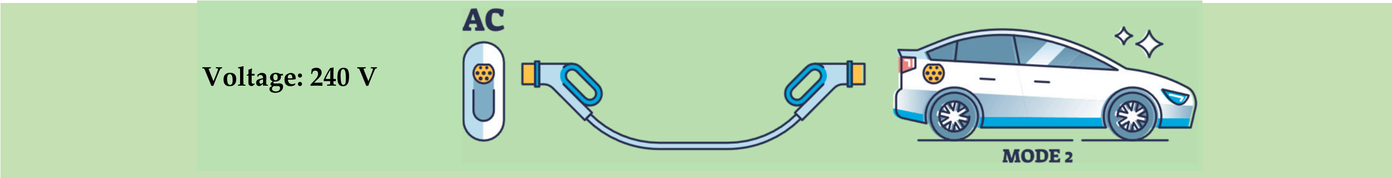
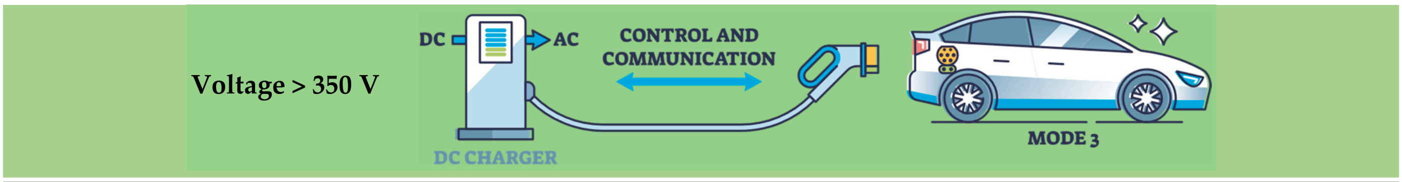
Year	Model	Energy Density	Capacity	Range per Charge	Full Charging Time	Ref.
	Voltage: 120 V					
2017	Tesla Model 3	~250 Wh/kg	~50 kWh (Standard) ~75 kWh (Long Range)	~350 km (Standard) ~500 km (Long Range)	40–50 h	[18,19]

Table 1. *Cont.*

Year	Model	Energy Density	Capacity	Range per Charge	Full Charging Time	Ref.
2018	Nissan Leaf	–	40 kWh	~240 km	2.5 days	[20]



Year	Model	Energy Density	Capacity	Range per Charge	Full Charging Time	Ref.
2017	Tesla Model 3	~250–260 Wh/kg	50 kWh (Standard) 75 kWh (Long Range)	~350 km (Standard) ~490 km (Long Range)	7–9 h (50 kWh) 9–10 h (75 kWh)	[18,19]
2018	Nissan Leaf	~220 Wh/Kg	40 kWh (Standard) 62 kWh (Long Range)	~240 km ~360 km	7.5 h (40 kWh) 11 h (62 kWh)	[20]



Year	Model	Energy Density	Capacity	Range per Charge	Full Charging Time	Ref.
2017	Tesla Model 3	~260 Wh/Kg	60–80 kWh	~500 km	24–39 min (SOC = 10–80%)	[18,19]
2019	Nissan Leaf Plus	~180 Wh/Kg	62 kWh	~360 km	45–60 min (SOC = 10–80%)	[20]

Optimization in charging techniques has become critical for effectively balancing charging speed with battery health and vehicle range. Optimization of traditional charging methods such as CC-CV and pulse charging can significantly improve battery performance and health. Different charging methods have been explored, such as CC-CV, pulse, multi-stage, and model-based charging. Other techniques, such as slow AC charging, fast DC charging, wireless charging, and rapid power exchanges, have improved battery health and safety [21]. Enhancing user convenience and integrating smarter charging solutions into infrastructure have recently been explored. For instance, wireless charging can offer a user-friendly alternative compared to traditional wired systems [22]. Vehicle-to-grid (V2G) integration with fast charging increases charger capacity by 10–17% to handle bidirectional energy flow, which can ensure that vehicles are fully charged within limited windows. It also reduces grid strain during peak demand. Studies have shown that up to USD 11,000 in annual savings can be achieved per electric school bus [23]. Wireless charging showed potential for supporting grid stability through V2G interactions compared to wired systems.

Additionally, advancements in wireless power transfer (WPT) technologies for EVs, including static and dynamic charging methods, are essential to making EV charging faster and more efficient [24]. Several companies, such as WiTricity [22] and Qualcomm Halo [25], have been working on EV wireless charging technologies to make charging more convenient, efficient, safe, and environmentally friendly [26]. Figure 1 demonstrates a static wireless charging system that transfers power through magnetic resonance between the primary and secondary pads. It integrates a battery management system (BMS) connected to the vehicle's controller area network for safe and controlled charging. The BMS regulates battery status and manages fast charging while minimizing human interaction. Therefore, this system can enhance safety and convenience in the charging process [27].

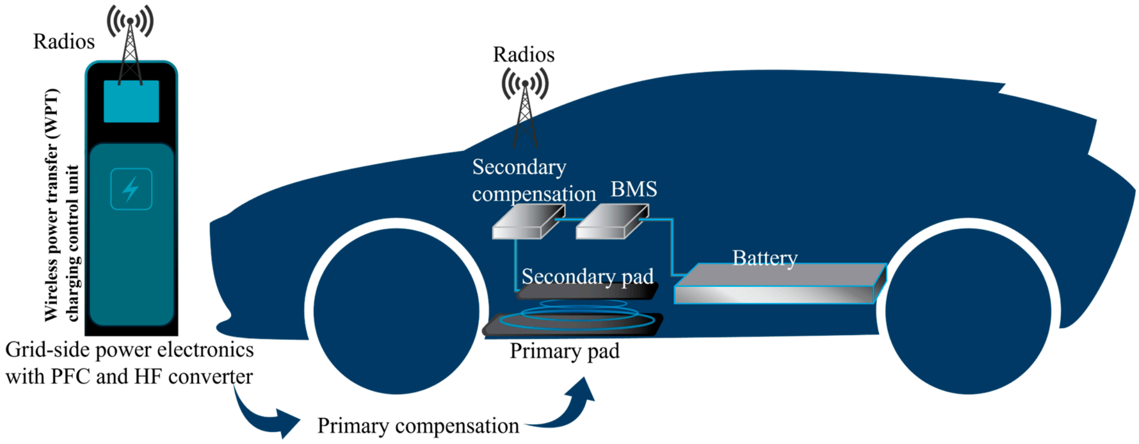


Figure 1. Wireless EV charging system: static wireless EV charging system with automatic control [27].

Although there have been several advancements in charging technologies to make EV charging faster and more accessible, it is essential to understand their impact on overall performance, particularly driving range. The driving range of EVs varies from 400 to 1000 km, depending on battery size and energy consumption. Several improvements to LIBs aiming to extended range and increase compatibility with high-speed charging infrastructure [7] have been explored. Table 2 illustrates current and upcoming EV models and their fast and ultra-fast charging potentials. For instance, models like the Yangwang U9 [28] and Zeekr 007 [29] have been engineered to recharge enough power for several hundred kilometers in about 10 min.

Additionally, the Toyota Crown [30] and SAIC-GM's upcoming models with Allegro technology [31] have charging times of about 20 min to reach an 80% charge. These examples highlight the industry's shift toward fast charging instead of refueling traditional vehicles [7]. Porsche is advancing fast charging technology through its Taycan model, which offers both flexible home charging with 11 kW and optional 22 kW AC chargers, which can significantly reduce charging times [32]. The Taycan can also charges quickly on the road, gaining 100 km of range in just five minutes at 800-volt high-power charging stations. Porsche has been expanding fast-charging infrastructure globally, and their goal is to establish charging parks with capacities of up to 350 kW [32].

Additionally, Nyobolt has developed an EV prototype ultra-fast charging battery that can charge 10–80% in under five minutes using a 350 kW DC charger [33]. These batteries, built with patented carbon and metal oxide anode materials, could offer fast charging without the degradation typically seen in standard LIBs. With a lifespan of over 4000 complete charge cycles, Nyobolt's technology addresses vital concerns regarding charge time and battery durability [33]. These advancements in fast charging technology support EV adoption and may be convenient for daily drivers. Similar innovations are now reaching heavy-duty vehicles, where rapid charging is essential for efficient operation.

Heavy-duty vehicles have also recently been stated to deliver up to 80% SOC within 20–40 min at charging power levels between 350 kW and 1 MW. For future developments, megawatt-scale chargers (up to 3.75 MW) are designed to reduce further charging time for long-haul trucks and buses [34]. This is particularly important for logistics and heavy-duty vehicles, where long charging times can severely disrupt operations, which delays supply chains. For heavy-duty vehicles like trucks and buses, where battery size can range from 200 kWh to 1 MWh, ultra-fast chargers (up to 1 MW) are necessary to keep charging times reasonable. For instance, a 500 kWh battery using a 350 kW charger would take approximately 68 min to charge to 80%. Recently, CHAdeMO and CCS have defined power charging levels above 350 kW and output voltages up to 1 kV and focused on the standardization process for fast-charging heavy-duty vehicles [14]. Thus, heavy-duty vehicle charging technology is advancing rapidly. At the same time, research focuses on improving fast charging for all EVs. Several parameters affect overall battery performance and lifespan, such as managing heat, reducing degradation, and ensuring safety.

Table 2. Overview of current and upcoming EV models using lithium-ion batteries and the corresponding characteristics.

Brand	Models	Battery Type	Range (km)	Capacity (kWh)	Charge Time	Ref.
BYD	Dolphin Comfort	Blade—LFP	427	60.4	~40 min (SOC = 10–80%)	[35]
		Blade—LFP	420	62	~29 min (SOC = 30–80%)	[36–38]
	Yangwang U9	800 V Blade—LFP Dual-charge	450	-	~10 min (SOC = 30–80%)	[39,40]
Tesla	Model 3	Cylindrical—LFP	507	75	~14 min (SoC = 10–80%)	[41]
		Cylindrical—NCM 811	515	120	~20 min (SoC = 10–80%)	[42–44]
	Model X	Cylindrical—NCA	539	95	~16 min (SoC = 10–80%)	[45,46]
	Semi Light (upcoming)	Cylindrical—LFP	–	75	~13 min (SoC = 10–80%)	[41]
	V3 Supercharging	NCA	~500	75	~15–20 min (SOC = 10–80%)	[46]
Mercedes-Benz	EQE	NMC	418	90.6	~32 min (SOC = 10–80%)	[47]
	VISION EQXX	NMC—silicon anode	1000	<100	~15 min (SoC = 10–80%)	[48]
	(EQS 450+) EQS Sedan/EQS SUV	NCM811 cathode	685	107.8	~30 min (SOC = 10–80%)	[49]
	High-Power Charging Model	NMC	-	~120	~15 min (SoC = 10–80%)	[50]
Volkswagen	ID.4	NCM	336–443	58–82	~29 min (SOC = 10–80%)	[51,52]
Ford	F-150	NMC	~515	98–131	~40 min (SOC = 10–80%)	[53,54]
	Mustang Mach-E	NMC	~505	70–91	~32 min (SOC = 10–80%)	[53,54]
Toyota	Crown, upcoming	Prismatic/new structure—LFP	1000	–	~20 min (SOC = 10–80%)	[55]
	Upcoming	Solid-state	-	-	~10 min (SOC = 10–80%)	[56]
Audi	e-tron Q4	–	~463	82	~28 min (SOC = 5–80%)	[57]
	e-tron GT (2023)	–	488	93.4	~22 min (SOC = 5–80%)	[58]
	Q6 e-tron (2025)	–	496	-	~21 min (SOC = 10–80%)	[59]
BMW	i7 eDrive50	NMC	575–611	101.7 kWh	~34 min (SOC = 10–80%)	[60]
		NMC	417–449	64.8	~29 min (SOC = 10–80%)	[60]
	i5 eDrive40	NMC	475	~83	<30 min (SOC = 10–80%)	[61]
Hyundai	IONIQ 6 (2024)	NMC	581	~77	~18 min (SOC = 10–80%)	[62]
Chevrolet	Bolt	NMC	417	65	~30 min (SOC = 10–80%)	[63–66]
	Blazer (2024)	NMC	~450	-	~10 min (SOC = 10–80%)	[63]
Nissan	Leaf	–	240–342	40–60	~40–45 min (SOC = 10–80%)	[67]
		NMC	348–465	63–87	~35–40 min (SOC = 10–80%)	[67,68]
	Ariya (2024)	NMC	~480	~87	~30 min (SOC = 10–80%)	[69]

The goal is to achieve 80% charge in under 15 min while maintaining high energy density and long battery life [70]. However, implementing fast charging technology presents several technical challenges, especially related to cell design [71]. The challenges are mostly related to high charging rates, which can generate heat, mechanical stress, electrolyte decomposition, lithium plating, localized hotspots, and uneven degradation [72]. Traditional fast-charging methods typically involve using high currents to charge the battery. The C-rate affects charging time for a 1 Ah battery; higher C-rates like 5C charge the battery in as little as 12 min, while lower C–C-rates like 0.05C extend the charging time to 20 h. Thus, it shows the significant impact of the C-rate on charging speed for fast charging applications [73]. However, high-rate charging results in capacity loss due to lithium plating [74]. Using the multi-stage constant current (MSCC) strategy for EVs showed that MSCC improved charging efficiency, battery health, and safety, especially for fast charging. Critical factors like charging stages and rates affect optimizing fast-charging techniques to extend battery life [8]. During fast charging, the higher initial rate capacity retention at the electrode level influenced the thermal profile and degradation. Both studies emphasized the need for carefully designed charging protocols to ensure long-term battery safety and reliability [75].

Several advancements have been discussed to improve EV fast and ultra-fast charging. For instance, the National Renewable Energy Laboratory (NREL) utilized advanced electrochemical models to study battery performance and degradation under fast charging [70]. These models are focused on lithium transport, microstructure effects on ion movement, electrolyte properties, degradation mechanisms, and adaptive charging protocols to improve battery designs. Innovations such as power converters, heat management systems, and wireless charging have been investigated to improve charging efficiency and reduce charging times [76]. However, there is a lack of research on design criteria to ensure uniform current distribution, minimize heat generation, and prevent dendrite formation during rapid charging cycles. This paper addresses these gaps by exploring fast-charging design criteria across multiple levels, from cell structures and module configurations to vehicle integration in packs and chassis. Various aspects, such as electrical, mechanical, and thermal properties, as well as safety and durability, are explored to provide a comprehensive view of structural LIB design needs in fast-charging EV battery systems. The design criteria are discussed, from internal cell design, through cell formats, to the design of cells in the EV chassis as a unique system. The structural characteristics of the electrical, mechanical, and thermal aspects are analyzed.

Additionally, the safety and durability of different cell formats are examined. Optimization techniques for designing cells are also explored to address the complex interplay in geometric configuration. Other configurations, such as modules, packs, and chassis integrations, are analyzed to optimize fast charging at the system level. This approach connects cell design with vehicle architecture, which is essential for developing fast-charging battery systems.

2. Internal Cell Architecture on Fast Charging

Internal cell architecture supports fast charging by higher current flow while maintaining long-term cell stability. Innovations in electrode design combined with advanced electrolyte formulations can reduce tortuosity, enhance ion transport, reduce heat, and minimize degradation [77]. Several parameters, such as the thickness of the electrodes [78], the type and arrangement of the separators, the electrodes' porosity, the electrolyte's design, and the configuration of current collectors, significantly influence fast charging performance. These parameters are thoroughly discussed in the following subsections.

2.1. Electrode Engineering

Enhancing ion mobility and reducing energy barriers is crucial for effective extreme fast charging. For instance, thicker electrodes can store more energy and improve charge capacity [79]; however, they pose quite a challenge in impeding the efficient movement of ions and increasing internal resistance during fast charging [80,81]. Reducing electrode thickness improves ion diffusion and transport, although it reduces the overall energy storage capacity [34,36]. The NREL stated that thin-electrode Li-ion batteries can charge in under 15 min but have 20% lower energy density and are twice as costly as thick electrodes. However, thick-electrode cells showed higher energy density but struggled with lithium concentration gradients during fast charging and accumulating lithium near the anode/separator junction [82]. Thus, a careful balance between electrode thickness and ionic conductivity is essential, as thicker electrodes increase active material, enhancing energy capacity. In a conventional design with 25 µm thick electrodes (Figure 2), only 56% of the volume is active material, while in thick electrode designs (200 µm), 88% is active. This reduces the space taken by non-energy storage components like separators and current collectors, thus increasing energy capacity without compromising safety. In thick-electrode designs, the separator takes up less space, 6% vs. 28% in conventional designs [83]. A study discussed optimizing the cathode and anode thickness of an NCM LIB (Figure 2). Energy density increased as both cathode and anode thicknesses increased, reaching a maximum of about 287 Wh/kg at a cathode thickness of 400 µm and an anode thickness of 190 µm, and then declined [84]. While thicker cathodes (up to 100 µm) can improve energy density by up to 50%, they negatively impact power density, which is critical for fast charging [85].

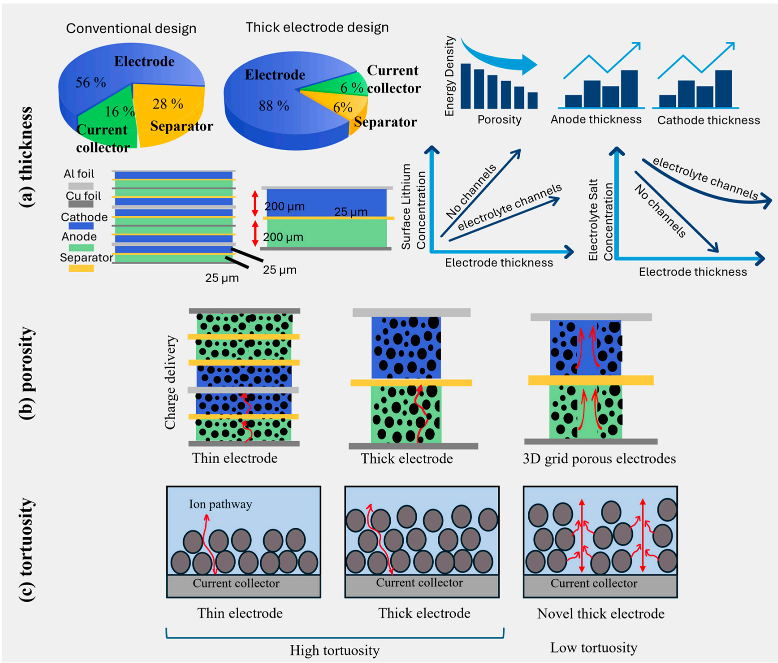


Figure 2. (**a**) Electrode thickness comparison: conventional vs. thick design and impact on energy density. (**b**) Effect of porosity on ion transport in thin, thick, and 3D grid porous electrode [86]. (**c**) Tortuosity reduction in novel thick electrode design, enhancing ion pathways for fast-charging [83].

Thicker electrodes can help achieve higher capacity for fast and ultra-fast charging if combined with optimized porosity and other design factors to facilitate efficient ion transport. These optimizations are necessary for the increased capacity of thicker electrodes, which come at the cost of slower charging speeds, and improved efficiency. Thicker electrodes make it harder for lithium to diffuse evenly. As can be seen in Figure 2a, cathode and anode thicknesses were optimized using RSM and BBD, finding that the 400 µm cathode and 190 µm anode maximized energy density (~287 Wh/kg), after which further increases led to declines. This increases the risk of lithium plating and reduces efficiency at high C-rates, like 5C, as shown in Figure 2 [82]. However, adding electrolyte channels improves ion diffusion by shortening transport paths, helping to distribute the lithium evenly, and reducing risks like plating, especially during fast charging [82]. Figure 2a [82] shows surface lithium concentration across the electrode thickness for different cells during a 5C charging rate following a 1C discharge. The challenge of high-rate 5C charging is that lithium ions accumulate near the anode/separator junction, especially for cells with thicker electrodes. It has been observed that cells without channels deplete Li^+ faster and have complications at a 1C discharge rate, while cells with channels maintain better salt concentration distribution due to shorter transport paths and increased separator surface area (Figure 2a). Thus, they have more efficient lithium diffusion throughout the electrode, as the channels reduce the polarization effect.

Another way to address the challenges of thicker electrodes is through multi-layer designs, which control porosity and enhance faster ion transport [87]. Higher porosity increases active sites for diffusion. However, it must be balanced to prevent structural degradation during cycling [88–90]. Li^+ ions must diffuse from the edges to the interior of graphite particles, leading to a longer diffusion path and slower ion movement, which affects charging speed. While more edge sites increase surface area and capacity, they also result in initial capacity loss. Optimizing graphite's structure, such as creating pores, shortens the Li^+ diffusion path, improving fast charging performance [91]. Strategies such as morphology adjustments, surface modifications, and optimizing solvents, salts, and additives will reduce activation energy [91]. Using molybdenum niobium oxide (MNO) anodes and optimizing electrode porosity improved the fast-charging capability of cylindrical cells and enabled 70% SOC in 120 s [92]. Optimizing the geometric distribution of active materials in NMC electrodes reduced resistance and provided more uniform ion flow, contributing to faster charging [93].

Another adjustment in thicker electrodes is the novel 3D grid porous electrode design, which features vertically aligned pores that reduce tortuosity and provide direct paths for Li-ion transport [86]. The novel 3D grid porous electrode design (Figure 2b) is compared to conventional thin and thick electrodes. Unlike conventional thick electrodes with tortuous ion pathways, the 3D grid porous structure has vertically aligned pores that provide direct paths for Li-ion transport. Thus, it improves Li-ion movement and fast charging performance compared to conventional thick electrodes, which have longer, tortuous paths for ions. Thick electrodes face challenges due to tortuous ion paths that hinder Li-ion movement. Thus, the novel 3D grid porous design reduces tortuosity in Figure 2c and improves ion transport and fast charging performance [86].

In addition to electrode thickness, lithium mobility is also dependent on the crystal structure of the cathode. Layered oxides, such as $LiCoaO_2$, have a two-dimensional (2D) structure with alternating layers of lithium and transition metal oxides. Such a structure allows lithium-ion transportation within the 2D planes with low diffusion barriers, which can be used for high ionic mobility and fast charging capabilities. However, these materials tend to structural instability during deep delithiation. A researcher observed that doped LCO achieved extremely fast charging (XFC) and maintained 91.3% capacity retention after 100 cycles at 5C [94]. In contrast, polyanionic systems like $LiFePO_4$ have a stable three-dimensional (3D) olivine-type structure, where lithium-ion transport occurs along one-dimensional (1D) diffusion channels. Therefore, layered oxides are generally better suited for fast charging applications, whereas polyanionic systems excel in terms of safety and structural robustness.

2.2. Electrolyte Engineering

Adjusting the parameters of electrolytes would further improve the charge transfer kinetics, hence better fast charging performance [95]. With regard to electrolytes, different aspects of fast charging should be considered, such as high conductivity, a high Li^+ transference number, low desolvation activation energy, strong reductive and antioxidative stability, good electrode compatibility, and a stable SEI layer [96]. Electrolyte additives can form a stable SEI layer, including low-viscosity co-solvents to improve ion mobility. For instance, a study found that adding 0.05 M $LiPF_6$ as an additive to a dual-salt electrolyte enhanced lithium metal batteries' fast charging and cycling stability [97]. Concentrated electrolytes can also improve ionic conductivity and reduce lithium plating risks, which is essential for fast charging capabilities [96]. A study showed that challenges in achieving 10 min fast charging in LIBs can be due to cathode cracking and poor electrolyte transport, which can be solved by using electrolytes and low-viscosity additives [77].

Although liquid electrolytes have been significantly improved, they still have safety-related risks, such as flammability and poor cycling stability, particularly under high charge rates. Solid-state batteries (SSBs) offer a promising alternative to address these challenges by replacing flammable liquid electrolytes with solid electrolytes, which are inherently safer and more thermally stable [98]. While solid-state batteries are not generally better for fast charging compared to liquid-based systems, recent innovations suggest they could have possible potential if challenges like ionic conductivity, interfacial resistance, and grain boundary effects are addressed. Recent developments in materials for solid electrolytes, such as garnet-type $Li_7La_3Zr_2O_{12}$ (LLZO) and sulfide-based electrolytes, have demonstrated ionic conductivities comparable to liquid electrolytes, especially for fast charging. For instance, by doping rubidium (Rb) at the lanthanum (La) site in the garnet structure, researchers achieved significant enhancements in ionic conductivity, reporting 1.62 mS/cm at room temperature and 4.56 mS/cm at 60 °C. Thus, garnet-type electrolytes can be a potential in advancing solid-state batteries for fast charging applications [99].

Despite the high ionic conductivity of sulfide-based solid electrolytes, they might face challenges with decomposition during operation, impacting interfacial ion transport and cycle life. By optimizing the voltage window, a study achieved a rapid 10 min charge/discharge at 6C and a lifespan of 600 cycles at 1C with 85% capacity retention, which could be hold potential for fast charging applications [100]. Another study proposed strategies to improve sulfide electrolytes for fast charging, including doping to enhance ionic conductivity, interfacial engineering to reduce resistance and stabilize electrode–electrolyte interfaces, and thin electrolyte designs to facilitate faster ion transport in fast charging [101].

SSBs can significantly reduce the risk of lithium dendrite formation, thus extending battery life. Companies like QuantumScape [102] are developing SSBs that can achieve 80% charge in 15 min and withstand higher voltages without degradation. In all-solid-state batteries, both solid electrolyte (SE) and cathode thicknesses are an important factor and must be 20 μm or less in order to achieve significant energy improvements [103]. However, optimizing both the SE and cathode thickness remains a challenge, especially in obtaining the required active material volume and N/P ratio for fast charging situations. The active material volume directly affects energy storage capacity. Higher volumes enable greater energy density, which is critical for fast charging, although efficient ion transport needs to occur without diffusion limitations. In the same way, an optimal N/P ratio has proper charge acceptance and reduces lithium plating. Figure 3a highlights the importance of solid-state electrolyte (SSE) thickness to enhance energy density in all-solid-state lithium batteries (ASSLBs) [103]. Reducing SSE thickness improved energy density and ion transport while requiring mechanical strength. Another advancement for high-energy

ASSLB is an anode-free sodium solid-state battery for faster charging, which was developed by the University of Chicago and UC San Diego to reduce costs and environmental impacts and prevent degradation seen in lithium-ion batteries [104]. The anode-free approach (as shown in Figure 3b) can eliminate the need for an anode by depositing sodium metal directly onto the current collector during charging [105]. This can prevent issues like dendrite growth and SEI layer formation. Figure 3c shows lithium dendrite growth in both liquid and solid-state electrolytes. In liquid electrolytes, dendrites grow from the lithium metal anode into the electrolyte, eventually reaching the cathode, which results in short circuits. Dendrites form along grain boundaries in solid-state electrolytes due to high electronic conductivity, which still allows for dendrite penetration despite the solid electrolyte's strength. Dendrite growth can be inhibited by optimizing the solid–electrolyte interface and employing materials with lower electronic conductivity to ensure safer and more reliable fast-charging solid-state batteries [106].

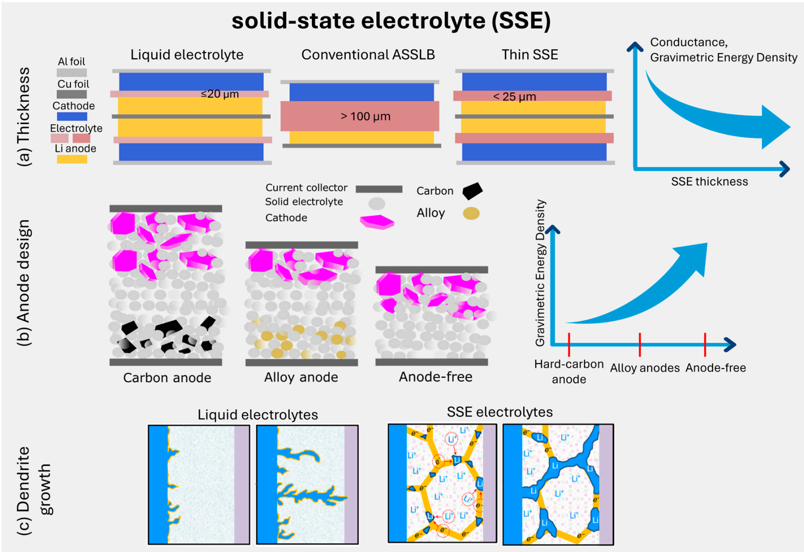


Figure 3. (**a**) SSE thickness variations [103], (**b**) anode designs (carbon, alloy, anode-free) and energy density (reproduced with permission [105]), and (**c**) dendrite growth comparison in SSE (reproduced with permission [106]).

2.3. Other Factors

Beyond electrolyte and electrode adjustments, parameters such as the cathode-to-anode impedance ratio and current collector design also play critical roles in mechanical stability and ensuring thermal safety. The cathode-to-anode impedance ratio helps reduce lithium plating on the graphite anode and improve current density distribution, which can minimize fast-charging risks [75]. Unlike electrode thickness, which mainly affects ion transport distance and energy capacity, the impedance ratio addresses electrical losses and maintains uniform current flow, which can impact charge efficiency and safety.

Reducing the thickness of current collectors is another factor to be considered. A 50% thickness reduction in 18650 cells enhanced mechanical flexibility and accommodated expansion during lithiation, contributing to better performance during fast charging by optimizing material packing and reducing resistance [107]. Microporous structures were also investigated in the current collectors by introducing micropores (2–10 μm for copper, 1–15 μm for aluminum). The surface area provided more electrochemical reaction sites, and charge/discharge efficiency was enhanced [108]. Moreover, a tabless current collector reduces in-plane polarization by up to 36% at 1C and fourfold at 3C, which could increase SoC by up to 23%. Similarly, a multi-tab current collector design improves current density distribution, which will be discussed later. It can significantly reduce thermal gradients and local hot spots, particularly in larger cell formats like 21700 and 26650 [78,109]. In addition to innovations in current collector designs that can optimize current flow and reduce resistance, advancements in separator technologies can enhance thermal stability and safety during high-power operation. Ceramic-coated separators improved thermal stability under high-power conditions, particularly in cylindrical and prismatic cells [110]. Advanced separators with a shutdown feature are designed to melt and halt ion flow if the cell's temperature exceeds critical levels to avoid electrochemical reactions that could lead to dangerous thermal events. Using multi-layer separators enhanced the safety of prismatic cells by providing multiple barriers to prevent short circuits and maintain thermal stability [111].

There have been other significant developments in the material development of battery cells for safety, performance, and longevity. For instance, the porous current collector (PCC) design for lithium-ion batteries is designed for fast charging and can maintain high energy density [112]. Unlike traditional impermeable current collectors, the PCC allows for Li^+ to pass through its porous structure and quadruple the diffusion-limited C-rate capability. It was found that this design can achieve remarkable fast charging performance: 78.3% SOC in 15 min (4C), 70.5% SOC in 10 min (6C), and 54.3% SOC in 6 min (10C) [112]. Moreover, the function of metallic current collectors against degradation [113] and separator design in preventing short circuits has been studied, showing that knowledge of failure mechanisms under stress can provide safer battery design. One of the most exciting innovation areas is the development of self-healing materials for LIBs, which are very important for battery longevity [114]. These materials can repair micro-cracks and other forms of damage within the battery after mechanical degradation. Another promising development is flexible and stretchable LIBs to enhance flexibility and resilience under mechanical stress [115,116]. Stretchable LIBs are composed of conductive polymers and graphene to maintain stable electrochemical performance in severe bending, stretching, or twisting conditions. Optimizing both cathode and anode interfaces through electrolyte engineering can prevent lithium plating, a significant issue in fast charging that affects battery efficiency and lifespan. Electrode engineering, balancing thickness, porosity, and material design, is essential to fast charging performance. Challenges like lithium plating and ion diffusion barriers are addressed through advanced designs for a safer and more efficient fast-charging battery.

Optimizing internal cell architecture is essential to obtain fast and ultra-fast charging. Electrode and electrolyte engineering and the characteristics of other components, such as the separator and current collector, must be carefully analyzed to handle higher currents without overheating or degrading the battery. Solid-state batteries might have the potential. However, some challenges remain in optimizing their design for fast charging. Next, we will explore the evolution of cell designs, especially past, present, and upcoming developments for EV applications.

3. Cell Design Advancements in Fast Charging

The most common cell formats include cylindrical, prismatic, pouch, and blade, and each has unique characteristics [117]. Understanding these formats' history, design, and specific performances provides valuable insights into battery systems, especially for fast-charging targets [118]. Different cell formats offer various advantages and challenges [119]. The following are the details of each cell format design advancements and their effect on fast charging.

3.1. Cylindrical Cells

Cylindrical cells were among the first formats commercialized, driven by the need for reliable, high-performance batteries for portable electronics [120]. Cylindrical cells (known as jelly rolls) are introduced in the early 1990s with Sony's 18650 cells [121]. The cells comprise a cylindrical can and a rolled-up assembly of the anode, separator, and cathode layers (Figure 4). A central current collector distributes a uniform current, the separator prevents short circuits, the vent releases pressure to prevent explosions, and the gasket seals the cell to avoid leaks. Insulation rings, placed at the top and bottom of the jelly roll, prevent electrical short circuits with the metal can [122]. The positive terminal or cap and the negative terminal or bottom provide good electrical contact and usually contain internal safety features, such as vents. The primary safety feature in cylindrical cells is usually the vent mechanism on top of each cylindrical cell [123]. Utilizing safety vents, the Sony VTC5 18650 and Ampking 20700 prevented explosions during thermal runaway, especially during fast charging [123]. Vent clogging from debris can lead to dangerous pressure buildup, but an improved venting path and maintenance of internal structural integrity can release effective gas and enhance safety [123]. The design can also include a current interrupt device (CID), which isolates the cell in case of excessive pressure buildup, and a positive temperature coefficient (PTC) device that, when overheated, limits current flow to prevent thermal runaway [124]. The PTC is designed within the cell [125], and it can limit the current flow when the cell temperature rises excessively. Thus, it acts as a fail-safe to mitigate risks of thermal runaway. Additionally, cylindrical cells include an internal pressure relief mechanism that provides an additional layer of protection, especially when internal pressure becomes too high, in order to reduce the risk of cell rupture [126].

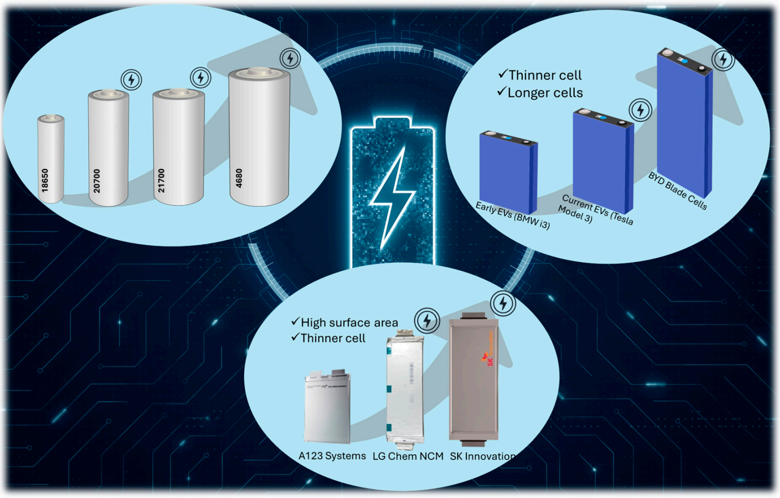


Figure 4. Evolution of cell formats: cylindrical cells (18650 to 4680), prismatic cells, and pouch cells.

3.1.1. Shape Factors

The most common cylindrical cell types, especially in EVs, are "18650", "21700", and "4680" [127]. Such shape factors, showing cell dimensions, are available at various capacities and energy densities. Larger formats like the 21700 and 4680 allow for higher capacity and energy density [128]. In addition, other cylindrical cell formats like "26650" and "32650" have also been used, especially in industrial applications that require higher capacities and durability. While the 18650 format is widely used for consumer electronics and EVs, larger formats like 21700 and 4680 have been developed to enhance energy density to reduce the number of cells for high-capacity applications. Figure 4 represents these cylindrical cell types, and Table 3 illustrates more details on the specification of cylindrical cells, such as their dimensions, capacity, energy density, weight, and charging time [127,129,130].

The 18650 cell format is extensively used in Tesla vehicles and other high-performance EVs [131]. The 21700 cell provides higher capacity and energy density [132]. In the latest innovation, 4680 cells potentially exceeded a capacity of 9000 mAh [133]. Based on our calculations, comparing the performance of a single Sony 18650 cell to Panasonic's 4680 cells, we observed a 5.1-fold increase in energy capacity, a 6.1-fold boost in power output, and a 20% enhancement in electric vehicle (EV) range.

The typical operating temperature conditions in cylindrical cell formats for discharging and charging are −20 to 60 and 0 to 45 °C, and the nominal voltage is about 3.6–3.7 V [134]. The development of these formats shows the growing requirement for better energy storage, thermal efficiency, and fast charging capabilities in EV applications. Larger formats like 21700 and 4680 are primarily applicable in fast and ultra-fast charging scenarios because they handle higher power densities. Panasonic Energy recently launched mass production for 4680 cylindrical lithium-ion cells, especially in EV battery technology. With five times the capacity of 2170 cells, these cells extend EV range while reducing the number of cells required per pack, thereby lowering production costs. The Wakayama factory will be the central hub for 4680 production, using advanced manufacturing techniques, and it aims to obtain zero CO_2 emissions through renewable energy [135]. This breakthrough positions 4680 cells as a key to making EVs more affordable and sustainable [135].

Table 3. Different cell format characteristics (cylindrical, prismatic, pouch, and blade cells).

Format	Types	Dimension (mm)	Capacity (Ah)	Energy Density (Wh/kg)	Weight (kg)	Charting Time (h)	Applications	Ref.
 **Cylindrical**	18650	D:18 L:65	2.5–3.5	~250	0.045–0.05	2–4	Laptops, e-bikes	[136]
	26650	D:26 L:65	3.5–5.5	~180–220	0.08–0.09	2–4	Power tools, e-bikes	[137]
	21700	D:21 L:70	4–5	~276–300	0.06–0.07	1–1.5	EVs, e-bikes	[138,139]
	32650	D:32 L:65	5–6	~100–150	0.09–0.1	2–4	EVs, power tools	[140]
	4680	D:46 L:80	6–9	~276–333	0.08–0.09	30–40 min	EVs	[141]
 **Prismatic**	-	L: 100–300 W: 30–100	50–100	150–250	0.5–2	4–8	Standard EVs Ex: CATL LFP Prismatic Cell, CALB 3.7 V 50 Ah L148 N50 A Lithium NMC	[142,143]
	-	L: 150–400 W: 50–150	100–200	200–300	1–3	4–8	Long-range EVs Ex: Samsung SDI 3.7 V 94 Ah NMC Prismatic Battery, EVLithium 135 Ah High Discharge Rate $LiFePO_4$ Cell	[144,145]
	-	L: 150–350 W: 40–120	10–100	120–220	2-min3	30–40 min	Fast charging Ex: Benergy 3.2 V 10 Ah $LiFePO_4$ Prismatic Cell (Fast Charge 5C)	[146]
 **Pouch**	-	H: 100–400 W: 100–300 T: 6–12	40–100	250–300	0.5–1.5	4–8	Standard EVs Ex: SK Innovation Battery E370 3.7 V 37 Ah Lithium NMC PHEV Battery Cell	[147]
	-	H: 200–500 W: 100–350 T: 6–15	60–100	250–300	0.7–2.5	4–8	Long-range EVs Ex: SK Innovation 3.7 V 75 Ah pouch cell	[148,149]
	-	H: 150–400 W: 100–350 T: 6–25	10 -80	150–300	0.5–2.5	10–30 min	Fast-charging EVs Ex: NMC+ 19 Ah, LFP 22 Ah, Nyobolt's upcoming pouch cell	[33,150]

Table 3. *Cont.*

Format	Types	Dimension (mm)	Capacity (Ah)	Energy Density (Wh/kg)	Weight (kg)	Charting Time (h)	Applications	Ref.
 Blade	-	L: 960 W: 90 T: 13.5	120–200	150–250	2–4	0.5–2	BYD LFP blade (3.2 V, 138 Ah)	[151]

Across all cell formats, the thermal, mechanical, and electrical characteristics of the design must be optimized for fast charging [152–154]. As cylindrical formats like 21700 and 4680 advance to support higher energy and fast-charging needs, effective thermal management and optimized tab design have become essential. Both factors can manage heat and ensure uniform current distribution, reducing resistance and enhancing charging efficiency. These design improvements enable safe, durable performance under the high-power demands of fast-charging EV applications.

Heat dissipation is one of the significant concerns in battery cell design. Cylindrical cells, like 18650, 21700, and 4680, have created a strong reputation for effective thermal management. The cylindrical shape provides effective heat dissipation through the outer metal casing [155]. This spiral-wound design contributes to shorter thermal pathways and quicker transfer of heat to the outer casing. Hence, the thermal path from the core to the surface is shorter. Larger cylindrical batteries might handle radial heat dissipation due to a larger surface area dissipating heat from the core. However, they may also suffer from temperature differences along the axial (lengthwise) direction because of higher thermal resistance in that direction. Smaller cells, like the 18650, will tend to lose heat more consistently along their length but can have issues with radial heat dissipation, so the temperature across the radius is not even [156]. Hotspots can be further minimized by cell geometry optimization and cooling strategies, which require a careful balance between heat management and cell size to avoid compromising battery performance [157]. The metallic casing of cylindrical cells further improves thermal conductivity to keep the cell stable and prevent overheating during fast charging [158]. It has also been illustrated that aluminum housing in cylindrical cells can contribute to fast charging capabilities. The higher thermal conductivity of aluminum than conventional materials, such as nickel-plated steel, improves heat dissipation [159]. Despite enhancing heat dissipation and current flow, the cylindrical shape might accumulate heat in the core, which results in temperature gradients [160]. The thermal optimization of a hybrid battery thermal management system (BTMS) using phase change materials (PCMs) showed enhanced heat absorption for 18650 cylindrical cells. This design efficiently manages heat during fast charging and could reduce cooling power demand by 27% while keeping the battery at a safe temperature (35 °C) [161]. A study on immersion cooling shows that this method can reduce the maximum cell temperature by up to 30% compared to traditional air cooling during ultra-fast charging cycles. Additionally, this method can prevent thermal runaway propagation between cells, especially during rapid charging [162]. For instance, the Carrar TMS for EV batteries uses advanced two-phase immersion cooling technology that can support fast and ultra-fast charging. It prevents heat spikes during charging, acceleration, and extreme temperatures, while significantly increasing the lifespan by 2–3 times and supporting ultra-fast charging in less than 5 min [163]. Besides advanced thermal management systems for ultra-fast charging, optimization of internal cell features like tab design further enables better performance. Optimized tab placements have also facilitated internal resistance reduction and thermal management improvement [11,164]. Further discussion on thermal management systems is illustrated for the battery system in the module and pack design section.

3.1.2. Tab Design

Tabs are placed in specific locations to connect a cell to the pack. The consequences are localized heating and inefficiencies, particularly in the case of fast charging wherein higher currents impact hotspots and resistance and could limit charge speeds in traditional cell designs. Optimized tab placements were found to reduce total polarization by up to 36% across different ambient temperatures, thus enhancing fast-charging efficiency [78]. During 3C-CC fast charging, the polarization across the cell was significantly reduced and increased the full SoC by up to 23% [78]. Various tab designs have been innovated to impact the fast charging capabilities of EV battery packs. Figure 5 presents different tab locations and configurations for different cell formats [165], which can affect battery performance.

For cylindrical cells (Figure 5), positive and negative tabs are placed on opposite sides in (a) and (b), which means a uniform current distribution that prevents overheating. In cases (c) and (d), both tabs are placed on the same side, and in case (d), an angled configuration is used, which improves the current distribution and is ideal for high-power cells due to lower resistance. For case (e), the tabs are too close, which could increase the risk of overheating and potential short circuits, and thus it might be a poor-quality design. For cases of (f), (g), and (h), multiple-tab configurations improve heat dissipation and reduce cell impedance, but designs with more tabs, like in (h), complicate the manufacturing process.

Various innovative tab designs were introduced to enhance the fast charging capabilities of EV battery packs. The multiple-tab design distributes electrical currents evenly across the cell. Thus, it can reduce local heat buildup by minimizing current crowding, especially during high charge/discharge rates, which improves the thermal performance of the battery. For instance, overcoming overheating and preventing lithium plating, a common problem related to fast charging at high currents, is not feasible without multi-tab designs, especially for larger cells such as the 26650 formats. In multi-tab configurations, electrode utilization becomes more homogeneous and reduces cold spots due to the temperature inhomogeneity where lithium plating occurs [78].

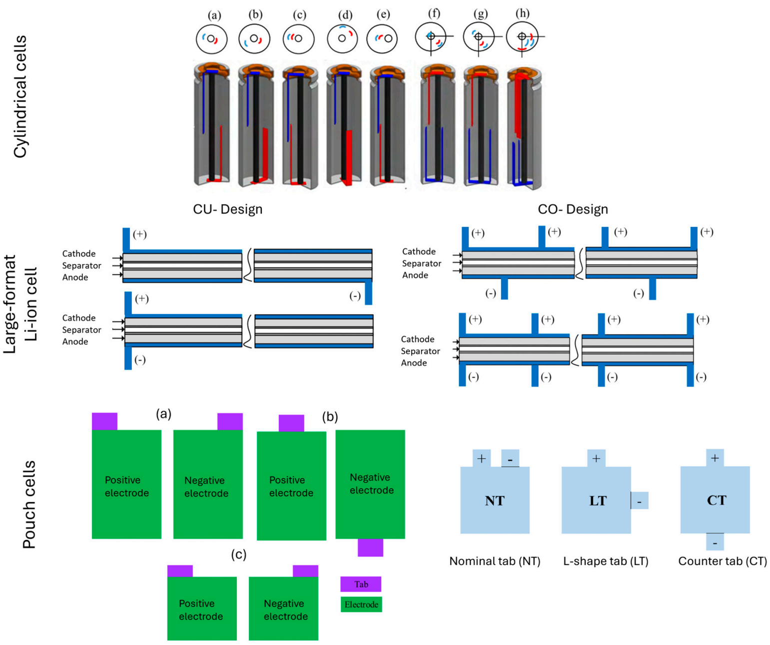


Figure 5. Multiple tab locations in different cell formats: (1) possible tab locations in cylindrical cells (2) Tabs on the current collector along the electrode length direction in large format Li-io cell (3) **Left**: tabs with different size in different location in pouch cell, and **Right**: Different tab types in pouch cell (NT, CT, and LT) (reproduced with permission [165,166]).

Multiple conducting tabs (4 to 12) in cylindrical cells reduced internal resistance, improved current flow, and reduced voltage loss [167]. The 21700 format typically uses multi-tab designs [168]. Another study found that increasing the number of tabs in 18650 cylindrical cells enhances fast charging performance by reducing internal resistance [169]. A greater number of tabs led to a 50% improvement in C-rate performance and extended battery life by at least 1000 cycles. However, there is a limit to the benefits, especially for smaller cells, where additional tabs do not continuously improve performance due to space constraints [169]. In traditional cell designs, tabs are placed at specific points to connect the cell to the pack. However, the localized connection points can cause uneven current distribution, which results in localized heating and inefficiencies. Transitioning from traditional segmented tab designs to an innovative tabless design in cylindrical cells reduced heat generation and polarization drops to enhance faster, more homogeneous charging [109]. Tesla's 4680 cell uses a continuous tab, eliminating the need for multiple discrete tabs to contribute to faster heat dissipation [128]. Thus, tabless cell designs or multi-tab designs are another critical innovation that directly impacts the fast charging capabilities of EV battery packs and leads to several advantages (Figure 6). Therefore, the cells can handle the high-power densities required for fast and ultra-fast charging. A full-tab configuration for large-format cylindrical cells improved internal heat management in another study. Validated models of such design achieved fast charging times of less than 12 min from 10 to 80% SOC [170]. In another study, expansive foil tabs and an electrolyte with higher ionic conductivity in 21700 cylindrical cells reduced charging time to 80% SOC by 46%, resulting in a fast charge of 25.5 min. However, faster charging increased cell aging by 39% [171].

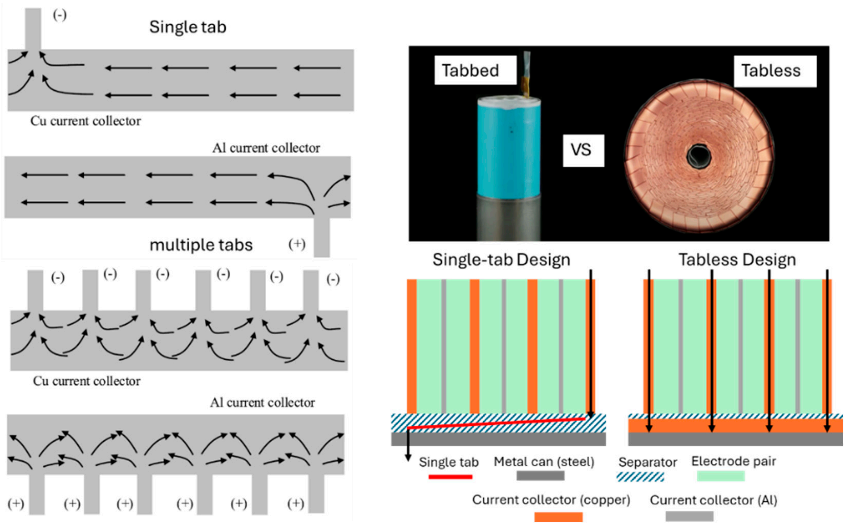


Figure 6. (**Left**) Electron transport path in the current collectors of a cylindrical cell in single pair of tabs and multiple pairs of tabs, reproduced with permission. (**Right**) Comparison of tabbed versus tabless designs in cylindrical cells, showing current flow in single-tab and tabless configurations [78,172,173].

Optimized cooling strategies, particularly tab cooling for tabless cells, have significantly boosted fast-charging efficiency in battery formats like 18650, 21700, and 4680. This enhances the battery's ability to charge faster without overheating. As a result, charging times are shortened by 4 to 10 min, allowing for the EV to charge in approximately 16 min. The quasi-tabless design, mainly for cylindrical cells, is another innovation that improves current distribution and reduces hotspots [168]. Tesla's quasi-tabless design of 4680 cells utilized plate-shaped tabs with no notching of 25% of the cathode and 30% of the anode. This resulted in faster current and heat transfer during rapid charging cycles [168].

3.2. Prismatic Cells

Prismatic cells were developed in the late 1990s and early 2000s due to the pressing demand to adapt batteries to electronic devices more compactly and into automotive battery packs [174]. This format was mainly driven by high energy density in a compact and robust design. Prismatic cells contribute significantly to EV applications' fast and ultra-fast charging capabilities [29]. For instance, SK On introduced a new prismatic battery in 2023 to improve their SF battery's ability to charge 80% in 18 min. The battery features advanced Z-Folding for safety and cell-to-pack (CTP) technology for better thermal management. SK On also showed cobalt-free batteries, cutting costs while maintaining stability, and improved LFP batteries with 70–80% efficiency at −20 °C, which can be implemented for fast charging conditions.

Moreover, SVOLT recently developed a prismatic cell design for fast charging, known as short blade technology, combining the energy density benefits of cylindrical cells with the cost and performance efficiencies of a prismatic format. Their design simplified production and enhanced fast charging capabilities, especially for charging rates up to 5C and 6C. Thus, they shorten charging times to as little as five minutes for substantial state-of-charge increments [175].

Additionally, SVOLT developed a 6C ternary prismatic cell using NMC chemistry for ultra-fast charging to charge from 10% to 80% in just five minutes with high-powered chargers of more than 250 kW. StoreDot developed prismatic cells with extremely fast-charging silicon-based technology and achieved a 10% to 80% charge in 10 min. The 80Ah capacity cells, scalable to 160 Ah, are silicon-dominant anodes that enhance energy density, optimize thermal management, and support ultra-fast charging for EVs [176].

In automotive applications, prismatic cells are often used directly in battery packs (compared to the traditional cell–module–pack design) for electric and hybrid vehicles due to their ability to be densely packed and efficiently cooled [177]. Prismatic cells consist of flat, rectangular packages (Figure 4) containing the anode, separator, and cathode layers stacked or wound inside [178]. The rigid outer casing, typically of metal or hard plastic construction, provides mechanical protection and helps retain the cell's shape [179]. This format offers a more efficient use of space within a battery pack and enables enhanced thermal management over cylindrical cells. Pressure vent safety is essential for safe venting of the built-up pressure inside the cell in case of overheating or malfunction [180]. Such tests are crucial for prismatic cells, which are usually applied in high-energy-density issues of critical safety importance. The design for stacked electrodes may result in almost uniform pressure distribution across the cell and less mechanical stress. Specifically, in prismatic cells, reinforcement of the internal structure and external frame provide much higher resistance against mechanical impacts and extend the battery's cycle life, especially with commercial EVs when operating under fast charging. On the other hand, proper alignment and pressure distribution across the electrodes are highly essential to maintain mechanical stability that can avoid delamination [181].

Prismatic cells come in various sizes and capacities for specific applications. Table 3 illustrates an average range of specifications such as dimension, energy density, weight, etc., especially for EV applications. The prismatic cell size (Figure 4) has increased to enhance capacity. However, it should be noted that reducing charge time in larger cells requires additional design optimizations, such as tab configurations. The wide, flat surface area of prismatic cells is more effective in dissipating heat, which is considered an important factor in high-rate charging for maintaining the integrity and safety of a cell [182]. However, prismatic cells may undergo thermal gradient distribution due to their larger dimensions and more geometrically complicated internal structure [183]. A detailed electrochemical–thermal model evaluated the impact of various fast charging conditions on large-sized prismatic LFP cells using different cooling techniques. It was found that dual-side cooling is most effective across all cell sizes for managing heat during fast charging [184]. In prismatic cells, the challenge is managing heat generation during fast charging to prevent thermal spread. One design is integrated flat heat pipes (FHPs) with bottom and side liquid cooling plates to reduce the maximum temperature to 35.1 °C with a 1.5 °C temperature difference at 2C discharge. This configuration can prevent the thermal runaway of prismatic cells under fast charging conditions [185].

Prismatic cells have undergone several updates to make them more practical for fast and ultra-fast charging, particularly heavy-duty electric vehicles with very high charge requirements. For instance, better jellyroll designs, from single to multiple jellyrolls, combined with tab placement optimization, are some of the critical features for achieving much-enhanced performance and cycle life of batteries under very high rates of charge [181]. Prismatic cells have longer current paths, which can increase internal resistance. Tabs in prismatic cells are typically placed at the top or bottom edges of the electrodes. Optimizing tab placement and size reduces resistance and heat generation [186]. For instance, the positive tab is repositioned to the opposite side of the cell to align the tabs directly across from each other. It was found that this design enhanced uniformity in lithium-ion concentration and SOC distribution. Two-tab placements have been designed for large-format Li-ion cells to optimize electrode material usage in lithium-ion batteries, as shown in Figure 5. In the case of CU design, both positive and negative tabs are on the same side of the current collectors, simplifying the current collection but potentially causing non-uniform current distribution. For the case of CO design positions, the positive tab at the leading edge of the aluminum collector and the negative tab at the trailing edge of the copper collector improve current distribution and thermal management. These designs reduce resistance and enhance performance, especially during high charge/discharge rates. By distributing the tabs along the length of the current collectors, the designs aim to reduce resistance and improve the efficiency of the current collection, leading to better performance, especially during high charge and discharge rates.

An increment in the thickness of the positive and negative current collectors also led to a more uniform distribution of battery characteristics, which resulted in less heat generation [187]. In a new prismatic cell design, a conductive casing with stacked cathode and anode layers is used, each with tabs that extend to the opposite ends (top and bottom) of the casing. This arrangement shortened the electron path and reduced internal resistance and heat buildup to improve efficiency and thermal management [188]. Similar to cylindrical cells, prismatic cells also feature a vent mechanism to release internal pressure in overpressure conditions. A novel manufacturing technology that incorporated backward extrusion and coining increased productivity and safety for the cells by ensuring the vent explodes at a predetermined set pressure that eliminates any possibility of explosions during quick charging [189]. While prismatic cells have seen significant advancements, pouch cells also offer promising potential for fast and ultra-fast charging applications, which will be discussed next.

3.3. Pouch Cells

Pouch cells emerged in 1995 as a flexible alternative to rigid cell formats [190]. The development was targeted at minimum weight, suitable for applications with critical space and weight consideration issues [191]. Pouch cells are used in various applications, including smartphones, tablets, laptops, and EVs. More detail on the specification of pouch cells and their development are demonstrated in Table 3. Pouch cells present unique challenges and opportunities, especially for fast and ultra-fast charging scenarios. Pouch cells consist of a flat, flexible, laminated package that contains the anode, separator, and cathode

(Figure 4), which is wrapped by a composite film of nylon, aluminum, and cast polypropylene (CPP) [192]. The thin, flat structure of pouch cells allows for efficient heat dissipation, a critical factor in enabling faster charging without excessive thermal buildup. However, this format requires robust external support within the battery pack to prevent mechanical damage, and the manufacturing process can be complex and costly [193]. They require further support to maintain structural integrity under stress. Pouch cells rely on flexible packaging materials and reinforced edge seals to handle the mechanical stresses of expansion and contraction during rapid charge cycles [194,195]. Because of the need for support for structural integrity, pouch cells are unsuitable for cell-to-pack or cell-to-chassis EV applications, as their flexible, soft casing characterizes them. The inability to use pouch cells in structural battery configurations presents a significant challenge in leveraging their lightweight and high energy density advantages within the latest EV architectures [190]. The future for pouch cells is still bright with the introduction of various new technologies like Sakuu's metal-free design, which can further reduce weight and cost [196]. This design eliminates metal connections and reduces weight and costs, potentially increasing energy density. However, integrating these cells into EV structures could be challenging due to their soft casing and the need for an additional protective system against gas pressure during charge cycles. If these challenges can be overcome, pouch cells could be of interest and become a more feasible option in the EV market [190]. Ionblox introduced lithium–silicon batteries with large-format 32 Ah pouch cells 2022 that can handle over 1000 extremely fast charge cycles with minimal degradation and utilize a pre-lithiated silicon monoxide anode [197]. It was reported that these cells can achieve 60% charge in just 5 min and 80% in 10 min. Moreover, Desten introduced ultra-fast charging lithium iron phosphate (LFP) pouch cells in 2023 that can charge from 20% to 80% SoC in only six minutes [150].

Pouch cells have inherently excellent in-plane heat dissipation due to their large surface area and thin profile. This enables effective through-surface heat transfer of the cell [198]. However, since the heat dissipation is less homogeneous in the through-plane direction, that is, through the cell perpendicular to the surface, temperature gradients and hotspots are possible. This can create an imbalance of stresses that will impact cell performance and safety during fast charging in pouch cells. The lithium diffusion may cause thermal expansion and, hence, the development of average strain to induce stresses in the separator of pouch cells [199]. Thermal management must address the issues of anisotropic heat transfer, which is very pronounced in the case of fast charging [200]. For instance, the hot region of pouch batteries can be adjacent to tabs due to higher current densities at these locations [201]. For instance, the hot region of pouch batteries might be near tabs due to the higher current densities there. Testing of large-format A123 Nanophosphate® AMP20M1HD-A 20 Ah pouch cells showed that surface cooling reduced average temperature and reduced the degradation rate but did so at the cost of delivering usable capacity under fast charge [202]. Tab cooling provided higher usable capacity but led to faster degradation due to increased temperatures. The cooling coefficient ratio was 18.90, indicating that tab cooling would result in a 19 times greater temperature rise than surface cooling, which accelerates degradation [202]. Thus, tab cooling was more effective for fewer than 2000 cycles. Therefore, the cooling method in pouch cell design is critical to balancing performance and longevity for fast charging.

Another study evaluated six different cooling channel designs (serpentine, U-bend, straight, pumpkin, spiral, and hexagonal) attached to pouch-type battery modules to maintain temperature control during high-discharge scenarios like fast charging. It was found that serpentine and hexagonal cooling channel designs attached to pouch-type battery modules demonstrated the best thermal performance, achieving a 3–16% improvement in temperature uniformity compared to other designs. This optimization will be crucial in the extension of pouch cell life and reliability at very high charge rates. Further, a pouch cell module for fast charging was developed, with cooling plates integrated for temperature control to within an accuracy of 1 °C at 5C charging. This thermal management system reduced peak loss by over 60% at higher rates for stable, ultra-fast charging performance [203].

Other aspects under study for pouch cells involve the geometry of the current collectors having maximum electrical conductivity with minimum weight. Some pouch cells have only one tab for both the anode and cathode. While simpler in design, this may lead to higher internal resistance and, more importantly, uneven current distribution, especially in the case of larger cells. This was achieved by the central positioning of tabs and their dimensioning in 55 Ah LFP/graphite large-format pouch cells [204]. In pouch cells, a centered tab configuration significantly reduces maximum temperatures during charging, making it a safer option [205]. Figure 5 also shows various tab configurations in pouch cells, including symmetrical and asymmetrical placements of the positive and negative tabs. These configurations affect how heat is distributed within the cell. For the pouch cells (Figure 5) in (a) and (c): the two tabs are placed symmetrically on the same side of the rectangular electrode. For pouch cells in (b): the tabs are placed in the center on opposite sides of the electrode. It was found that a tab placement in the third configuration results in a lower maximum temperature while charging; therefore, it is safer. This may be because having the tabs opposite to each other can reduce the current concentration in one region; heat distribution becomes more uniform across the cell, which minimizes hotspots. This highlights the importance of tab positioning for better thermal management and overall safety [165,205,206]. In the case of counter tab (CT) placement and position, where both positive and negative tabs are centered, the best performance was achieved, especially for fast charging (Figure 5) [166]. The optimized CT design minimized the temperature difference (ΔT) and reduced the cell's internal resistance because the hot spots were distributed more uniformly. In the meantime, it showed a 7.3% lower capacity fade after 1000 cycles compared to the previous one, which best fits longer life and fast charging. Furthermore, the optimized CT reduced SEI film resistance and provided lower temperature distribution, thus improving overall cell performance.

An optimized counter tab (CT) reduced the cell internal temperature differential and potential gradient, which resulted in a more uniform temperature distribution (Figure 5). This optimization not only improved the uniformity of the temperature distribution but also contributed to the efficiency and speed of charging, with a minimization in ohmic heat, towards the extension of life and capacity retention upon multiple charge/discharge cycles. Considering tab sizes (60 and 30 mm) and their placements (opposite sides versus same side) showed that larger tabs on opposite sides led to a more uniform temperature and depth-of-discharge (DOD) distribution and an enhanced cell energy density of up to 10% at a 4C discharge rate [207]. These improvements in pouch cells minimize internal resistance, enhance temperature uniformity, and ensure consistent discharge distribution, especially for high-rate charging applications. Similar considerations can be applied to blade cells, which are gaining interest due to their unique design and high structural integrity, which could hold promising potential for fast charging.

3.4. Blade Cells

Blade cells, characterized by their elongation, were introduced by BYD in 2020, representing a recent advancement in LIB technology. The flat design enhances both efficiency and safety in EV batteries [38]. The structure allows for them to stack efficiently within a battery pack, creating a much higher energy density of over 50% compared to traditional designs. It also enables better thermal management through increased surface area for heat dissipation. Further specifications on blade cells are illustrated in Table 3. The blade-like shape also enhances the mechanical stability of the battery pack, reducing the risk of damage during impacts [38]. LFP has been typically used, which offers higher thermal stability and safety compared to other lithium-ion chemistries, making them well suited for fast and ultra-fast charging applications [38]. The blade cell design also allows for higher charge and discharge rates, which are required in EV applications. The blade shape offers mechanical support and minimizes the possibility of mechanical failure under thermal expansion and contraction [208]. Blade cells optimize performance through ultra-thin electrodes that reduce ion transport distances, which can be promising in improving ion transport and energy density [209]. The long, thin design of blade cells provides extensive surface area for heat dissipation, thus enhancing thermal management capabilities.

One of the significant features of blade cells is their rigorous safety testing. They have passed the Nail Penetration Test (the most stringent test for battery safety) without releasing smoke or catching fire, while the surface temperatures remain between 30 and 60 °C [38]. The Blade Battery's honeycomb-like aluminum structure contributes to its safety and improves mechanical rigidity and durability during fast charging. Blade cells are designed to integrate better with vehicle cooling systems [210]. However, maintaining uniform heat distribution across the entire length of the blade cell can be challenging [38]. The blade-like shape of these cells ensures efficient current distribution and reduces internal resistance, which could improve power output [210]. While BYD Han EV and BYD Tang EV [211,212] are among the first to use blade cells, more EVs are expected to adopt blade cells soon. Although the fast-charging time for the Blade Battery is approximately 50 min to reach 80% charge, this is considered highly efficient for a battery of its type and size [213]. Although their flat structure offers enhanced stability, further improvements are needed to minimize the risks related to internal mechanical stresses during fast charging.

In summary, various cell formats, such as cylindrical, prismatic, pouch, and blade, have been designed and optimized to meet the evolving demands of EV applications, especially for fast and ultra-fast charging. Cylindrical cells offer robust thermal management and mechanical stability, with innovations like the 4680 tabless design significantly improving fast charging performance. Prismatic cells provide higher energy density and space efficiency while requiring optimized thermal management to handle fast charging safely. Pouch cells have a flexible design and provide high energy density and customizable shapes but face challenges with mechanical stress. Blade cells have improved energy density, thermal management, and stability. However, the charging speed is not quite fast enough. Other battery technologies currently provide superior performance. For instance, Nyobolt's cylindrical 18650 cells featuring niobium technology are designed to achieve ultra-fast charging capabilities. Specifically, they can charge from 10% to 80% in under five minutes when using a powerful 350 kW (800 V) DC fast charger [214]. In addition to the cell design, their integration into the EV system also affects their charging performance, which will be discussed thoroughly in the next section.

4. Battery Assembly System in Fast Charging Design

The previous sections described the design and optimization of cell formats for fast and ultra-fast charging. This section focuses on the larger configurations, including modules, packs, and chassis systems, which significantly affect the overall battery system's thermal, electrical, and mechanical performance, especially in fast and ultra-fast charging scenarios. The arrangement of cells within modules, packs, and chassis systems is important during fast and ultra-fast charging in different aspects such as thermal, electrical, and mechanical performance. It includes conventional configurations, such as cell–

module–pack arrangements, and advanced designs, like cell-to-pack (CTP) and cell-to-chassis (CTC) systems.

4.1. Module and Pack Design

In the cell-to-cell process, as a conventional configuration, cells are assembled into modules and then into a larger battery pack. In fast charging situations, the battery's performance is greatly affected by how the cells are arranged within the module and pack [215]. For instance, General Motors' Ultium platform demonstrated a modular and flexible battery system that supports ultra-fast charging conditions [216,217]. This modular flexibility is beneficial in balancing charge distribution and maintaining consistent charge efficiency across the pack. These packs come in different module numbers: 12-module packs for trucks and 6-module packs for compact EVs. Ultium uses large-format, pouch-style cells that can be stacked horizontally or vertically inside the module. The 800-volt configuration of Ultium requires less current to deliver high power and hence minimizes resistive heating [216,217].

As the demand for quick-charging, high-energy-density batteries increases, safety will be crucial across all levels of design, from cell format to chassis integration. Smaller cells can afford much better safety and cost efficiency, but their more significant numbers complicate assembly because of the interconnections. Larger cell formats might be managed thermally and electrically. However, heat dissipation would be a challenge that could affect performance and safety [218]. Efficient current collection and distribution across the cells is critical for reducing resistance and ensuring safety during fast charging. The busbar design is a conductor in EV battery packs that distributes electrical current, which is essential for handling high currents and managing heat for safe charging. Electric vehicles face high currents and generate heat issues during charging. Thus, busbars or tab-to-busbar connections require materials that can work to manage heat when fast charging.

Connection strategies (parallel or series connections) significantly impact the ability to handle high currents and improve the speed and efficiency of the charge [219]. Most EVs use series and parallel connections, although some arrange groups of cells in parallel to enhance capacity before connecting these groups in series to achieve the required voltage level. This hybrid arrangement enhances the battery's performance characteristics to meet specific needs. The spatial arrangement of cells within the pack plays a substantial role in heat dissipation and structural integrity. For instance, optimized cell stacking or layering can improve heat transfer, reduce hot spots, and increase the mechanical durability of the pack [220,221]. These include four common battery connection configurations: series, parallel, series followed by parallel, and parallel followed by series. These configurations are crucial in designing EV battery systems to find the best trade-offs between power delivery and energy storage. The charging strategy of EVs controls the current and voltage profiles, thus optimizing ion transport, reducing heat generation, and preventing problems such as lithium plating and thermal runaway, especially in fast charging. The challenge mainly concerns balancing high charging speeds with battery safety and longevity [21]. Figure 7 shows the design and configuration of a lithium-ion battery pack for electric vehicles and critical components such as the busbar for power distribution and various battery cell arrangements. The busbar is illustrated as a central component for distributing power efficiently within the battery pack, which can minimize electrical resistance and improve overall efficiency [21].

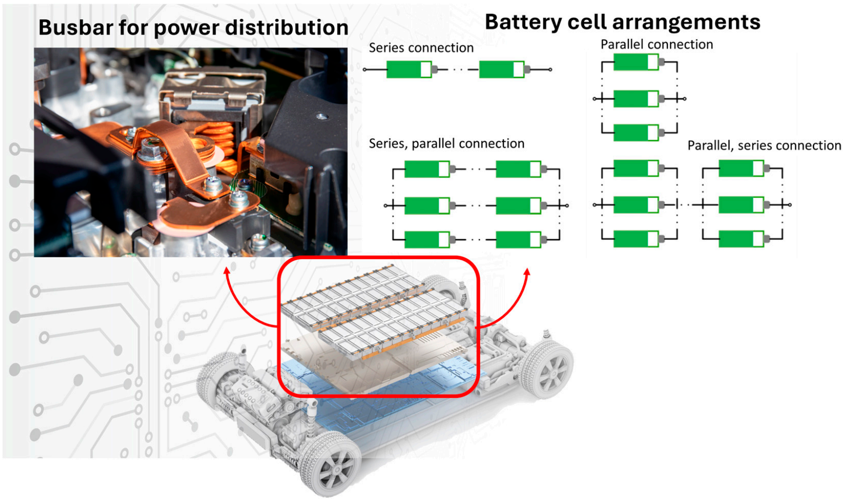


Figure 7. Importance of cell arrangement and busbar design in EV battery packs, illustrating efficient power distribution and various cell configurations (reproduced with permission [21]) for optimal performance [219,222,223].

Another critical factor in the development of EVs is the design and structural considerations of battery systems [223]. Mechanical protection plays a crucial role in the safety of battery cells, especially in large-format designs. A model has been introduced to understand the weak points in the battery structure to reinforce specific areas to enhance safety and prevent failures like short circuits and overheating [224]. Critical design parameters, such as component dimensions, wall thicknesses for module and pack housings, and the placement of longitudinal and cross beams, are necessary to ensure the structural integrity of the vehicle frame [225]. The battery module and pack are subjected to significant mechanical stress during ultra-fast charging. Adequate component dimensions and wall thickness can dissipate the heat generated during fast charging, while robust longitudinal and cross beams provide mechanical stability and protection for the battery pack. These design elements contribute to maintaining thermal equilibrium, reducing deformation under stress, and preventing damage. Several companies, such as Bayblend and Makrolon, have presented various solutions for optimizing wall thickness in battery modules and pack housings, reaching flame resistance at reduced dimensions down to 0.75 mm. These materials ensure efficient thermal management and structural integrity during ultra-fast charging. Safety and performance are enhanced by maintaining thermal equilibrium and reducing deformation under stress [226].

The brick module is a novel arrangement for integrating battery cells directly into the chassis of EVs. In contrast to the conventional in-line configurations, in which cells are arranged in a single row, the brick module arranges cells in an offset pattern. The staggered management of the brick module can mitigate the risk of thermal runaway due to overheating that can affect adjacent cells. It was found that this design could spread out the heat generated by each cell more evenly, thus preventing thermal runaway from propagating across the battery pack. Although the model can reduce the volume energy density compared to the traditional in-line setup (by less than 3%), it mostly enhances the overall safety and stability of the battery system [227].

Fast charging has developed at high temperatures, so heat management has become a great concern to avoid thermal runaway. Most modules and packs are integrated with cooling systems such as cooling plates, liquid cooling channels, or airflows. These systems distribute heat more effectively and minimize thermal gradients and overheating situations. Several cooling strategies, including air cooling, liquid cooling, and PCMs are discussed to address the issue of heat generation during fast charging to avoid overheating and thermal runaway [228]. Different cooling techniques, such as cold plates, PCMs, and refrigerant and immersion cooling, have been implemented for the BTMS [229]. Air-cooling systems in EV batteries are used for their simplicity, cost-effectiveness, and low maintenance. However, their low heat removal capacity could result in non-uniform temperatures between cells, especially in fast charging situations. This cooling system can be seen in models like the Nissan E-NV200 and Kia Soul EV [73]. In contrast, liquid cooling systems use water–glycol solutions or dielectric oils to efficiently manage heat, especially for fast charging and battery longevity. The integration of cooling plates at different strategic locations within the battery pack is shown in Figure 8, which shows how cooling plates are integrated at various strategic locations within the pack. Further improvement in thermal management is introduced with internal microchannel cooling, which directly targets heat generation at critical points, such as at the center of the cells and inside the battery, where overheating is likely to happen during fast charging [230].

Another option is the concept of a hybrid thermoelectric cooling (TEC) system combined with both liquid and forced-air cooling techniques [231]. This hybrid uses copper holders in an acrylic container to achieve a possible cooling of as high as 20 °C above liquid cooling alone, enabling the operating temperature of the batteries to below 30 °C during normal use and below 60 °C in high-demand conditions, hence fit for fast charging application. A parallel liquid cooling system with a seven-channel design for prismatic battery modules was introduced to improve fast charging capabilities and thermal safety. This innovative system enhanced volume energy density by dedicating less space to thermal management and allowing more room for active materials within the battery module. Thus, the system reduced energy costs by 26.9% while improving thermal safety during fast charging [232].

In addition to the cooling systems, phase change composite (PCC) materials, such as wax–graphite composites, manage heat passively, ensuring uniform temperatures and improving battery performance during fast charging [73]. PCM can absorb and conduct heat, especially under high heat conditions such as fast charging [233]. Embedding cylindrical batteries and cooling tubes into PCM (Figure 8) revealed a significant reduction in the maximum battery temperature, by 38 °C. Considering the cooling effect and processing cost, the optimal number of liquid-cooled tubes was nine [234]. Inserting metal fins or using fillers like copper mesh, graphene, and carbon nanotubes into PCMs also improved the thermal conductivity of the BTMS. This enhancement supported PCM more efficiently managing heat during high-temperature charging by absorbing and dissipating heat during low-temperature conditions and releasing stored heat to stabilize battery temperature, leading to better thermal regulation [235].

There have been innovations regarding the conventional module and pack design for fast charging capabilities. However, these might have some drawbacks, particularly regarding energy density, assembly complexity, and cooling efficiency. Recently, the industry has been slowly shifting toward cell-to-pack or cell-to-chassis design, whereby cells are directly integrated into the battery pack or chassis without intermediary modules. More details are discussed in the next section.

4.2. Cell-to-Pack Design

The integration of cells directly into the battery pack, along with advanced cooling systems, could result in a denser cell arrangement, optimize space within the battery pack, and improve gravimetric energy density. Techniques like CTP and CTC are substantial in the design and performance of EVs as shown in Figure 9 [236]. This design not only increases energy density by reducing redundant materials, but it also simplifies electrical and thermal management performance. This method would be applicable for fast and ultra-fast charging applications. By eliminating module casings and internal connections, more cells can be packed into the same space, improving energy density, especially for long-range capability with ultra-fast charging. According to the manufacturer's statement, the new CTP technology allows for an increase in specific energy by ~10–15%, an increase in energy density by ~15–20%, and a reduction in the number of parts for forming a battery pack by ~40% [227].

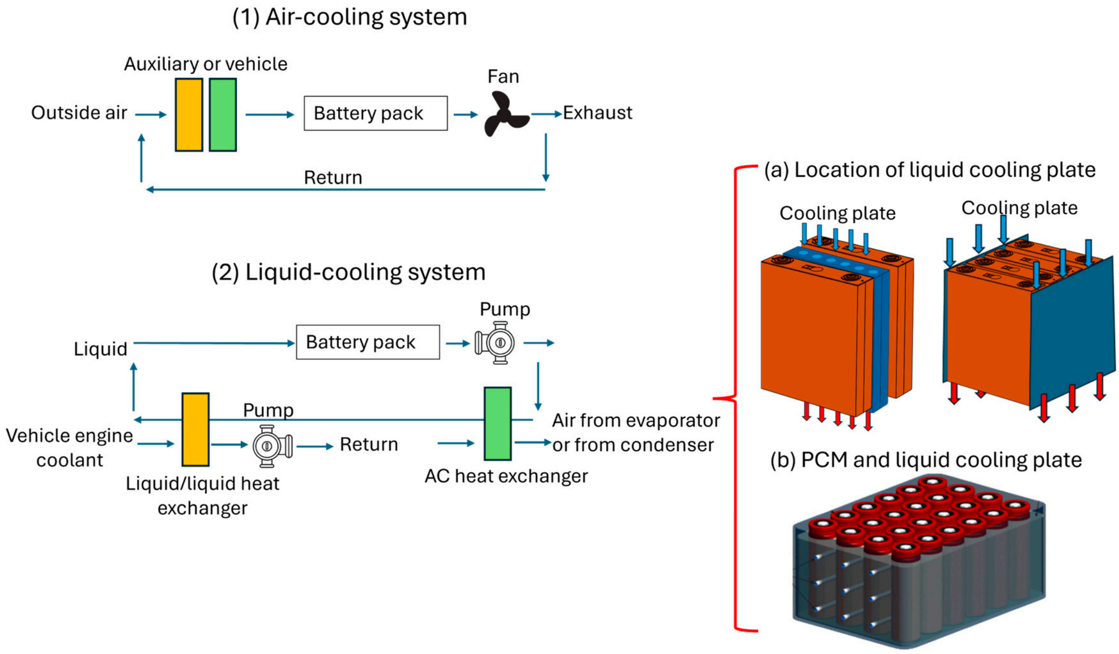


Figure 8. Battery cooling system configurations in EV: (1) air cooling and (2) liquid cooling methods for battery modules and pack (with enhanced cooling strategies such as optimized placement of cooling plates and integration of PCM for efficient thermal management) [230,234].

Several companies have been implementing CTP technologies to enhance battery performance, energy density, structural efficiency, and fast charging capabilities. In 2019, BYD deployed this technology to make high-capacity LFP batteries featuring characteristics of flatter and narrower cells and customizable lengths, which enhanced the energy density. Shortly after, CATL announced the first mass-production CTP system, which increased the energy density by 15–20% by removing the normal structural components in battery modules, thus reducing the number of components required by 40% and increasing production efficiency by 50% [237,238]. StoreDot announced that its CTP technology enables rapid charging, 80% SOC in 10 min [239]. NIO's 100 kWh CTP battery boosts energy density by 37%, extending range to 615 km and enabling faster charging, with a 500 kW charger that charges 10% to 80% in 12 min. Improved thermal management and an intelligent BMS ensure the best overall performance and safety. Volkswagen AG used CTP due to its simplicity and cost-effectiveness in weight reduction with standardized cells [228]. That includes using one battery cell across the board to minimize the complexity of the battery structure and lower the overall part count. Li Auto intends to install CATL's 4C Qilin battery third-generation CTP technology in its future BEV models. Compared to the volume utilization of conventional systems, this advanced system increases it from 52% to 72%, enabling high energy density up to 255 Wh/kg for NMC batteries and 160 Wh/kg for LFP batteries to realize more than 1000 km of range. Key innovations such as a water cooling plate and micron bridge connections improve durability for fast charging and increase safety by improving thermal management [240,241]. In addition, BYD has a standardized mounting system for easy and quick assembly and compatibility within a broad field of vehicle types [242]. A study on the BYD Han EV ZunGui 2020 highlighted the economic benefits of CTP designs in recycling and maintenance, showing a significant reduction in disassembly costs when moving from manual to fully automated processes [243]. Considering all these benefits, CTP adoption has accelerated, with the number of models in China using this technology rising from 13 in 2021 to 57 by October 2023, significantly increasing its market presence [244].

However, there have been challenges for mechanical stability and minimizing deformation in CTP battery packs during fast charging. Recent studies have focused on optimizing installation methodologies for the cells to enhance their stiffness and structural integrity. For instance, it has been shown that prismatic cells glued to the pack increased the stiffness of the pack, substantially reducing the deformation by up to 40% compared with an empty battery pack [245]. The larger contact area of prismatic cells was thus made more rigid to keep stability and minimize deformation under fast charging conditions. In contrast, the optimized fastening in pouch cells could enhance the mechanical performance in a particular direction during high-power charging events [245].

Apart from the mechanical stability improvements, proper thermal management is also crucial in CTP systems, which helps maintain appropriate battery performance and safety, especially when the batteries are fast-charged. StoreDot developed its CTP technology by embedding a structural cooling system inside the battery pack. I-beam-shaped cooling channels improve thermal management even under ultra-fast charging conditions [239]. The StoreDot technology can add 100 miles in as little as 5 min.

Directly integrating cooling systems such as embedded cooling plates in CTP design allows for more effective temperature regulation across the battery pack, especially during high-power charging [246]. For instance, a study demonstrated that embedding cylindrical batteries and cooling tubes into PCMs reduced the maximum battery temperature by 38 °C during fast charging [162]. Another key development in CTP battery technology evolution was the creation of thermally conductive urethane adhesives. These adhesives now allow for the direct bonding of cells to cooling plates, significantly improving thermal management and efficiency. For instance, DuPont's BETAFORCE™ 2800 TC adhesive has been applied to the Audi e-tron SUV. During operation, it can keep the batteries' temperatures at 25 °C and below 60 °C while 150 kW fast charging, thus prolonging the life and increasing the range of the batteries [247]. In order to improve the thermal management of CTP systems further, various cooling configurations have been investigated in several studies. A parallel air-cooling system with secondary vents reduced the maximum temperature difference of the battery pack by about 42%, depending only on the flow configuration change [248]. Thermal behavior research on CTP systems specified that using a thermal resistance grid for temperature calibration can effectively improve internal temperature distribution by reducing calibration time by over 60%. It was identified that the ambient temperature and driving speed are the dominant factors affecting the peak temperatures of the CTP cells, especially under fast driving and charging operating conditions critical to enhancing electric vehicle safety and efficiency. A parallel air-cooling system with secondary vents was designed to reduce maximum temperature differences within the pack by about 42% through improved flow configuration. Despite their simplicity and low cost, air-cooled systems have been phased out gradually due to failures in meeting large-capacity batteries and fast charging technology demands for heat dissipation [234].

4.3. Cell-to-Chassis Design

In EV design, the "Flat Pack" or "Floor Pack" configurations place batteries within the vehicle floor, spreading the weight and lowering the center of gravity. Based on these principles, CTC technology integrates batteries into the chassis to enhance space efficiency, structural rigidity, and thermal management (Figure 9). Thus, CTC design would be quite effective for fast and ultra-fast charging applications. Although CTC is a new technology, a few companies have advanced in this area. In 2020, CATL announced a development roadmap for CTC technology aiming for the beginning of large-scale mass production by 2025 [249]. CATL's CTC technology integrates batteries directly with the vehicle's chassis, increasing driving range and efficiency [250]. For instance, CATL's Shenxing Superfast Charging Battery uses CTC principles, adding up to 400 km of range in 10 min [250]. The volume utilization and energy density are especially emphasized as being the best for CATL's CTP 3.0 (Kirin Battery) to support a 1000 km range and 4C fast charging [251]. Tesla has been working on consolidated battery technologies, especially with its 4680 cells, and has been focusing on CTC and MTC to enhance energy density while reducing overall vehicle weight and materials and production costs. MTP and MTC designs operate at 30–90 V maintenance voltages, which is suitable for standard applications, while CTP and CTC require voltages over 100 V for high-energy demands [252]. CTC technology by Tesla connects battery cores or modules directly to the vehicle's chassis, which increases the Z-axis space in the car and leaves room for further integration enhancements [253].

In 2020, Tesla introduced its CTC technology. This ambitious approach integrates the battery housing into the underbody structure of the vehicle, comprising the rocker rail and the transverse and longitudinal beams and floor. The result is a vehicle lighter by 10%, components reduced by 370, and unit cost cut by 7%. This contributes to much-improved range and less overall weight in the Model Y from the Tesla Gigafactory produced in Texas [244]. Moreover, Leapmotor's C10 employs CTC technology within its LEAP3.0 platform to achieve a 420 km WLTP range that could support 400 kW fast charging [254]. This third-gen design reduces parts by 20%, cuts structural costs by 15%, and expands battery cell space by 14.5%. Integrating the battery, chassis, and underbody into a single structure increases vehicle range by 10%, torsional stiffness by 25%, and improves NVH performance. This efficient, space-saving design will help enhance safety and manufacturing simplicity [255]. CTB is a technology developed based on CTC principles to embed the battery cells into the vehicle body. It saves space and offers higher structural strength potential, which can contribute to enabling fast and ultra-fast charging. Xiaomi introduced its SU7 model in December 2023 with proprietary CTB technology to optimize spatial efficiency [256].

From a thermal management point of view, the chassis acts as a large heat sink. It can effectively dissipate heat across a broader surface to maintain uniform temperatures and prevent hotspots during high-power charging. Passive and active cooling systems can be integrated into the chassis to improve thermal performance. On the other hand, considering the aspect of space utilization, the design of CTC frees up valuable space within the vehicle. Heat transfer modes in the TRP of CTC systems have been studied using a 3D model, and thermal insulation strategies were evaluated to avoid TRP. According to the above results, increasing insulation thickness and improving cooling can effectively reduce the risks of TRP, setting new safety standards for CTC battery systems, which is so much more relevant for fast charging situations since, in that case, there is a huge accumulation of heat [257]. XING Mobility's CTC (cell-to-chassis) battery system integrates immersion cooling technology directly within the chassis [258]. In this design, the battery cells in CTC are fully immersed in the dielectric fluid, which cools each cell directly. While doing so, thermal management increases significantly due to fast charging since these cells' temperatures are even, overheating is minimized, and higher currents can be allowed to charge without risking degradation. Implementing immersion cooling within the CTC architecture enhances the overall efficiency and safety of ultra-fast charging applications for high-performance electric vehicles [258]. For instance, XING Mobility's IMMERSIO™

CTC solution uses immersion cooling to keep battery temperatures 20–30 °C lower than traditional methods for faster charging due to a reduction in thermal stress. This design can support rapid charging, take the battery from 20% to 80% SOC in under 15 min, and reduce charging time by up to 50% [258].

Further innovations have also been developed in battery integration that enhance structural integrity. Another significant improvement in CTC design is in load-bearing capacity through distributed battery integration compared to traditional centralized systems. The optimized chassis design, which utilized different minimum battery spacings (e.g., 40 mm to 70 mm), demonstrated that reducing the battery spacing increased the stiffness of the overall structure. Additionally, mechanical performance can be enhanced through load optimization within the cells and volumetric utilization by allowing for hybrid battery geometries that use a combination of cylindrical and cuboid cells.

In summary, integrating cells into modules, packs, and even chassis is important for fast charging in battery assembly systems. Several factors, such as electrical connections, thermal management, and structural integrity, must be optimized at the module and pack level to take on high charging rates without overheating while maintaining their performance. Technologies like CTP and CTC have been focused recently on increasing maximum energy density and fast charging capabilities by minimizing internal resistance and optimizing space and thermal management. Innovative cooling techniques and further structural integration improvements have enhanced heat management capabilities and further supported the concept of fast and ultra-fast charging in EVs.

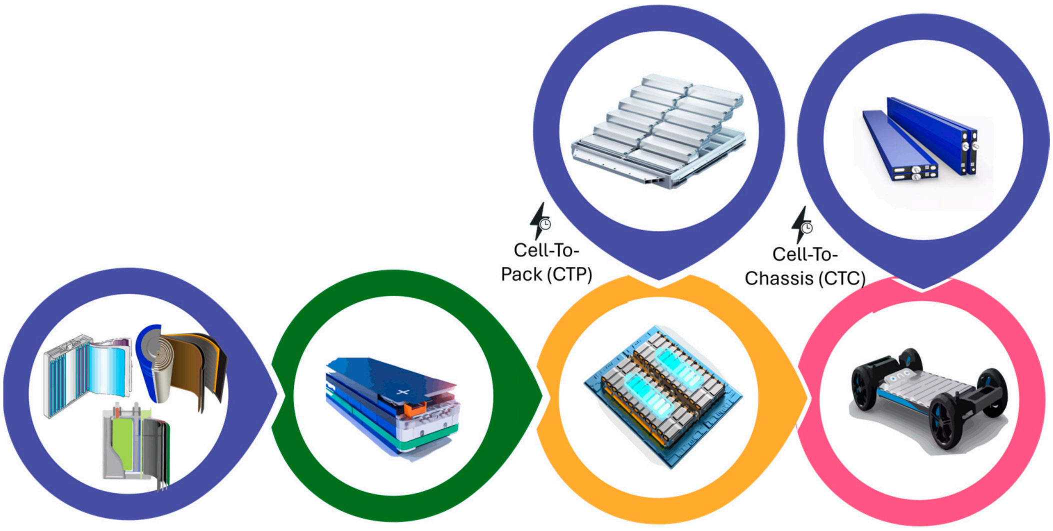


Figure 9. Progression from battery cells to integrated pack and chassis system and advancements in CTP and CTC technologies for enhanced efficiency and fast charging in EVs.

5. Concluding Remarks

Fast and ultra-fast charging have become essential for the widespread adoption of EVs due to the increasing demand for shorter charging times and longer ranges. With the growing EV market, consumers expect more convenience and less downtime. Fast and ultra-fast charging require a multi-dimensional approach to address several effects, from cell design to system-level integration and safety. This paper addressed the challenges in optimizing EV battery design across various levels. The impact of electrode and electrolyte engineering and innovative cell structures, like anode-less designs, on battery performance during fast charging were discussed. We reviewed the evolution of cell formats, including cylindrical, prismatic, pouch, and blade. Their mechanical, thermal, and electrical characteristics were also analyzed in terms of their fast charging support and effectivity.

Beyond cell design, system-level solutions for fast charging were explored. Different configurations like cell-to-pack (CTP) and cell-to-chassis (CTC) greatly have impacted fast and ultra-fast charging. More details on the effect of each level are demonstrated as follows:

1. Cell internal level

Advancements in cell structure, especially in electrode, electrolyte, and separator technologies, can significantly impact lithium-ion batteries' fast and ultra-fast charging. Reducing electrode thickness facilitates faster charging by shortening ion transport pathways. However, it can reduce energy density by up to 20%. Advanced architectures such as porous and 3D grid electrodes increase surface area for ion diffusion and reduce charging times. Innovations in electrode materials, like silicon–carbon nanocomposites, minimize internal resistance and prevente dendrite formation, which is crucial for safe, high-speed charging. The multi-layer design and structured porosity of the electrodes allows for improved lithium-ion distribution to avoid lithium plating at high charging rates of 5C and above. The safety of solid-state electrolytes replacing liquid ones may allow for even better ion transport at faster rates. However, their properties and thickness are essential to maintain stability and conductivity when electrolytes face such intense conditions during charging. Ultra-thin, high-thermal-resistance separators can also help fast ion conduction, while ceramic-coated separators provide stability under elevated temperatures above 60 °C. Optimization of internal cell architecture is needed to meet fast and ultra-fast charging requirements for EVs.

2. Mid-level cell format

Cell design advancements across formats, including cylindrical, prismatic, pouch, and blade cells, have substantially impacted designing batteries for fast and ultra-fast charging demands in EV applications. Cylindrical cells, particularly the latest 4680 format—which includes table designs and improved thermal management and charge efficiency—could reduce charging times by up to 12 min for 10–80% SOC. This setup enables efficient heat dissipation and uniformly distributed current, which is highly required in fast-charging high-power applications. Configurations like multi-tab and tabless show better current pass-through, less internal resistance, and cell temperature rise, especially under high-power charging conditions. In their compact and stackable outlook with tab placement improvements and cooling channels, prismatic cells are designed toward increased energy density with efficient heat dissipation. For instance, ultra-fast charging up to 6C rates for the short blade prismatic cells from SVOLT reduces the time to 80% SOC in roughly five minutes. Supported charging rates are up to 6C, reaching 80% SOC in about five minutes.

For pouch cells, the flat design allows for efficient surface cooling, which is essential for fast charging. Innovations in tab placement, such as multi-tab and centered-tab configurations, have improved thermal stability and uniform current distribution, especially in large-format cells. Blade cells, introduced by BYD, offer robust safety, enhanced energy density, and better heat distribution. Their unique shape enables efficient mechanical stability and thermal performance.

3. High-level assembly integration

The fundamental improvement to battery assembly systems in module, pack, and chassis configurations has greatly improved EVs' fast and ultra-fast charging capabilities by optimizing thermal management, charge distribution, and structural stability. The design and optimization of the modules and packs in battery assembly for fast charging are based on electrical connections, cell arrangement, and structural integrity. For instance, busbar design using copper tabs is relevant in reducing electrical resistance and minimizing heat generation during high-power charge cycles. Additionally, cells can be spatially arranged within the pack to minimize hotspots and further optimize overall charging efficiency. The structural elements include reinforced walls and optimized module dimensions to maintain mechanical stability under the stresses of fast charging. CTP technology has been used to integrate cells directly into the pack, optimizing energy density by avoiding redundant structural material. The CTP design by StoreDot can achieve fast charging up to 80% SOC in 10 min because the company has integrated cooling solutions into the batteries through even heat distribution. Other CTP designs, such as NIO's 100 kWh battery, enhance the vehicle's range while allowing for faster charge times because compact and efficient designs meet energy and fast charging requirements.

Besides CTP, the technology behind CTC maximizes space utilization and thermal management and has the added advantage of structural rigidity. It acts like a large heatsink, where the chassis dissipates heat over a wider area to avoid hotspots and maintain uniform temperatures during high-power charging. CTC systems, like XING Mobility's IMMERSIO™, further enhance fast charging with immersion cooling technology, reducing battery charging time by up to 50% while maintaining lower cell temperatures that support safe ultra-fast charging. The optimized battery spacing and hybrid cell geometries increase the load-bearing capacity and durability of the unit, thus improving the stiffness of the chassis and distributing mechanical stress more effectively.

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