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Electrode Structure and Its Impact on Commercial 18650 Lithium-Ion Battery Performance: A Comprehensive Review

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Abstract

Lithium-ion batteries (LIBs) are widely used for energy storage, and their functionality is directly related to electrode structure. The article analyzes how electrode thickness, porosity, and material composition affect the overall performance of 18650 LIBs. The report also provides a comparison of the various commercialized electrode types and their effects on energy density, charging/discharging rate, and cycle life. The article explores the correlations among electrode structure, ionic transport, reaction kinetics, and thermal stability, and provides meaningful insights into the key factors that can be considered among the most glaring determinants of battery efficacy. By summarizing the current evidence, this review suggests that optimizing the electrode structure can significantly increase output and lifespan of 18650 LIBs and, consequently, their ability to be utilized in high-performance energy storage systems.

Keywords

Li-ion battery, 18650, Electrode thickness, Porosity, Electrode structure, Energy storage

1. Introduction

Lithium-ion batteries (LIBs) have become the preferred energy storage device due to their high energy density, extended cycle life and versatility in that they can be adopted in many applications such as portable electronics, electric vehicles (EVs) and renewable power storage devices (Ngoy et al., 2025)(Kong & Pecht, 2023). Not to mention the fact that the 18650 cylindrical cell geometry is widely used in the commercial market because it is space saving with sound mechanical robustness and has a credible performance profile which is critical in harsh applications like the automobile and the large-scale power storage applications (Baazouzi et al., 2023). Due to the growing importance of having batteries which can be highly efficient and longer lasting in performance, it is necessary to tune key characteristics of the electrode morphology like the thickness of the electrode, porosity and the composition of the material in order to improve the battery's performance (Khan et al., 2025a).

Electrode thickness is also one of the significant design parameters utilized in the improvement of the performance of the LIBs. The battery's energy density may be increased by making the electrodes thicker, which will increase the amount of active material. This comes at the cost of higher internal resistance, less ion diffusion and slower charge/discharge rates (Li et al., 2022). Conversely, Thinner electrodes on the other hand may improve ion motion and higher rates of charge/discharge but decrease the battery's energy density. Thus it is a thin line that must be toe in terms of choosing the optimum thickness of the electrode to be utilized in a given application (Kang et al., 2022) .
Besides the thickness, the porosity of electrodes also plays an imperative role in ion transport. Increased porosity ensures easier movement of electrolytes with increased ion mobility necessary for rapid charge/discharge feature. Increased porosity may cause structural failure of the electrodes that account for the mechanical breakdown and deterioration in the long run (Haverkort, 2019). The design of the electrodes should be such that the porosity is optimized in such a manner that the ion diffusion is adequate and at the same time mechanistically strong (Yang et al., 2022a).

The other major parameter deciding the efficacy of the LIBs is the material composition used in the electrodes. Graphite and silicon-based composites become increasingly popular in the form of anode materials and Nickel Manganese Cobalt (NCM) and Lithium Iron Phosphate (LFP) become increasingly popular in the form of cathode materials and become determinant of the battery's electrochemical properties, cycle life and rate characteristics (Dai & Panahi, 2025; Yu et al., 2025). Material choice may significantly affect energy density, heat behavior and battery safety. Researchers also keep innovating new and superior materials like graphene and silicon anodes to improve battery performance in the areas of conductivity, stability and energy density (Feyzi et al., 2024; Ni et al., 2024).

The effect of the thickness of electrodes on the performance of LIBs has also remained a highly discussed topic in recent literature. The optimization of the thickness of electrodes to attain the highest achievable energy density without the loss of the fast discharge and charge characteristics has also been studied by Khan et al.(Khan et al., 2025b) in their recent work. Boyce et al. (Boyce et al., n.d.) also studied the impact of thickness and porosity on the electrochemical and heat characteristics of lithium-ion batteries and suggested that the amalgamation of the parameters is the cornerstone in the accomplishment of the charging of batteries within a short time frame. Patel et al. (Patel et al., 2023) also analyzed the impact of structural variations in the design of the electrodes on the fast charge characteristic of commercial 18650 cells and indicate the importance of precise structuring of the electrodes in the usage of cells with high power.

Battery performance is also highly influenced by the material composition of the electrodes. Zheng et al. (Zheng et al., 2023a) talked about the issues and methodologies of using the thicker electrodes in LIBs, especially in energy storage. Geng et al. (Geng et al., 2024a) also examined the effects of electrode thickness and charge rate on the overall electrochemical performance with emphasis on the trade-offs between energy density and charge/discharge rates.
Furthermore, high porosity gradients and multi-scale electrode designs have been explored in order to improve the rate capability and cycle life of LIBs. The benefits of gradient porosity in the design of electrodes were identified by Yang et al. (Yang et al., 2022b) who demonstrated that optimized porosity could improve the fast-charging characteristics of LIBs without compromising the structural integrity. Guo and Yao (Guo & Yao, 2020) also pointed out the significance of the thickness gradients in the improvement in the performance of Si-based anodes such that the innovations can be exploited in the development of high-performance LIBs with higher energy densities and stability. Furthermore, the heat characteristics of the electrodes also become critical at the battery design phase, particularly in applications with higher power. Xu et al.(Xu et al., 2016) investigated the SOC sensitive mechanical features of the electrodes and the thermal stability of the LIBs which provided details regarding the role of the structure of the electrodes in the generation and dissipation of heat. The performance of the commercial 18650 cell was also compared

by Zatta et al. (Guarnieri et al., 2024) which also gave details regarding how the structure of the electrodes affects the electrochemical performance along with heat management.

Hence, to improve the performance of commercial 18650 lithium-ion batteries in general, the electrode structure should be optimised in terms of thickness, porosity, and material composition. This review is an overview of the recent advances in the design of electrodes with the emphasis on the understanding of how the different aspects impact the battery's electrochemical behaviour, heat behaviour, and rapid-charging properties of lithium-ion batteries. The findings shall be used in providing guidance in future research and development in the construction of the high-performance LIBs to be used in electric vehicles, renewable sources of power storage, among other applications with large demands.

2. Structure of 18650 Li-ion Battery

The 18650 Li-ion battery with an 18mm outer diameter and 65mm length; this has been chosen due to the large energy density, long cycle life and reliability (Kong & Pecht, 2023). The battery's performance and the battery's safety depend on the battery's structure, and the battery's structure consists of many basic products such as, electrodes, separator, electrolyte and design features. The internal structure of a 18650 Li-ion Battery is illustrated in figure 1. There are numerous variants of cathode materials which were used in 18650 batteries. Some of them are lithium cobalt oxide ($LiCoO_2$), which is a high energy density material (Duh et al., 2020); lithium manganese oxide ($LiMn_2O_4$) (Chen et al., 2024), which is thermally stable and safe; lithium nickel manganese cobalt oxide (NMC), which is a balanced material; and lithium iron phosphate ($LiFePO_4$), which is highly thermal and has a long cycle life. The most widespread anode materials are graphite, silicon-graphite composites and lithium titanium oxide (LTO). Graphite is very specific with a high cycle stability, and it can be plated in lithium high charge rates. LTO has the advantage of being very safe and fast charging with the disadvantage of low energy density (Sandhya et al., 2014).The separator is usually constructed from polyethylene (PE) or polypropylene (PP), with ceramic-coated separators giving more excellent thermal stability and safety. The separator is an essential component that electrically separates the anode and cathode while enabling ionic conduction to conduct(Kaenket et al., 2023). Solutions of organic solvents such as ethylene carbonate (EC), dimethyl carbonate (DMC), or diethyl carbonate (DEC) containing lithium salts such as lithium hexafluorophosphate ($LiPF_6$) are known as electrolytes. These solutions are moderated in regard to viscosity, ionic conductivity, and stability and they usually have additives that enhance performance and safety. Table 1 shows the battery specifications of different commercial 18650 Li-ion batteries. Figure 2 presents a radar chart for each cell, evaluating energy capacity, energy density, low-temperature capacity retention, voltage drop stability, and temperature rise. Evaluation is conducted on quartiles so that each cell can be readily judged in relation to the others based on each characteristic.

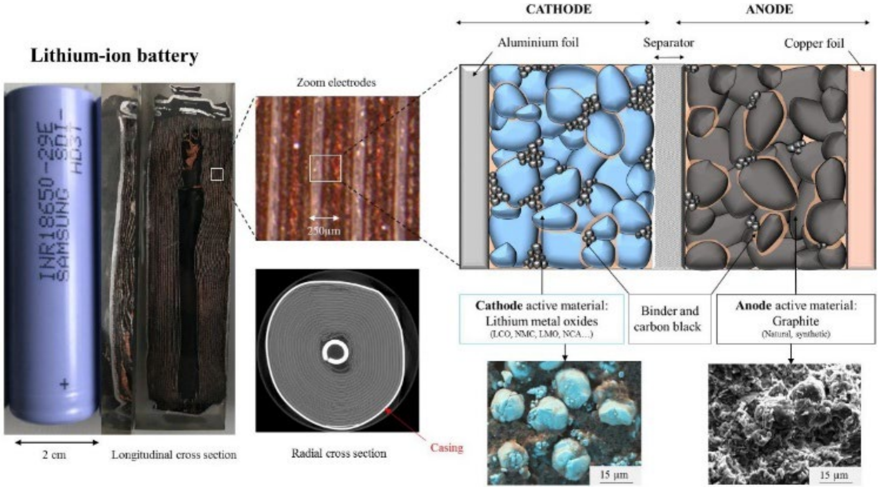


Figure 1. Internal Structure of 18650 Li-ion battery (Vanderbruggen et al., 2021)

Table1: Properties of different commercials: 18650 Li-ion batteries (Lain et al., 2019)

Properties	A123 M1A	LG HB2	LG HG2	LG HB4	Samsung 25R	Samsung 30Q	Sony VTC5A	Sony VTC6
Anode material	Graphite	Graphite	Graphite +Si	Graphite	Graphite +Si	Graphite+ Si	Graphite+ Si	Graphite +Si
Cathode material	LFP	NMC-532	NMC-811	NMC-111	NCA& NMC-622	NCA	NCA	NCA
Weight (g)	39.8	43.1	44.8	43.1	43.8	45.8	47.9	46.9
Volume (cm^3)	17.0	16.8	17.0	16.7	17.0	17.1	16.9	17.3
Cathode (cm^2)	794	848	929	778	1036	1032	1024	952
Anode thickness (µm)	36	44	55	43	43	45	47	53
Cathode thickness (µm)	81	43	52	50	38	44	43	52
Anode porosity	25%	23%	25%	24%	21%	25%	27%	38%
Cathode porosity	26%	28%	17%	26%	9%	9%	13%	15%
Electrolyte mass ($gA^{-1}hr^{-1}$)	5.2	2.8	1.3	3.0	1.8	1.4	1.8	2.1
Power density ($KWkg^{-1)}$	2.5	2.6	1.6	2.6	1.7	1.2	2.3	1.6
Energy density ($Whrkg^{-1}$)	83	131	246	132	216	245	196	246
Rated Capacity (Ahr)	1.1	1.5	3.0	1.5	2.5	3.0	2.5	3.0
Disch. Current (A)	30	30	20	30	20	15	30	20
Power: Energy (W:Whr)	27.3	20	6.7	20	8.0	5.0	12.0	6.7
Discharge Capacity (Ahr)	1.011	1.526	3.021	1.535	2.569	3.089	2.56	3.163
Discharge energy (Whr)	3.28	5.65	11.01	5.71	9.46	11.23	9.36	11.52

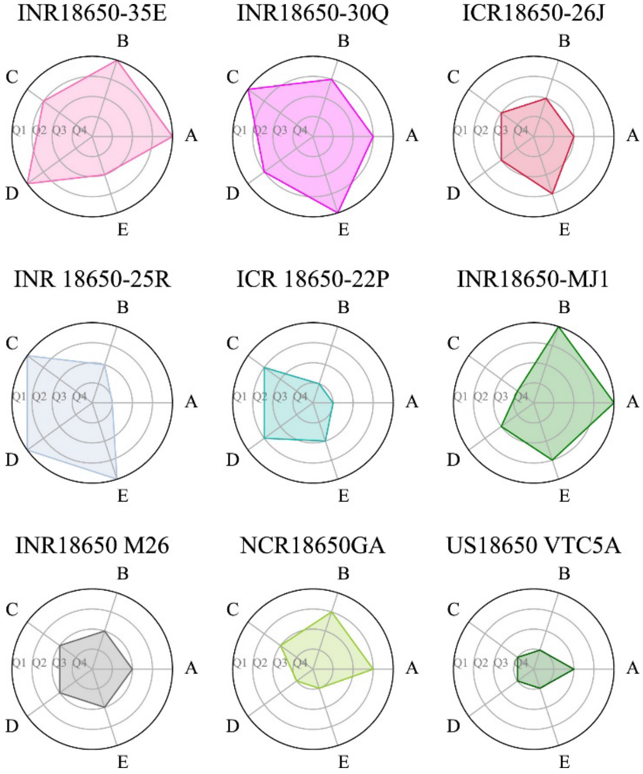

INR18650-35E
INR18650-30Q
ICR18650-26J
INR 18650-25R
ICR 18650-22P
INR18650-MJ1
INR18650 M26
NCR18650GA
US18650 VTC5A

Figure 2: Radar charts of performance of each cell of the battery. A: Energy, B: Energy density, C: Capacity retention, D: Voltage drop, E: Impedance rising.(Casado et al., 2025)

3. Effect of Material Composition on Performance of 18650 Li-ion Batteries:

The efficiency of commercial lithium-ion batteries (LIBs) depends mostly on the composition of the cathode material and anode material. Cathode materials that are highly energy dense like Lithium Cobalt Oxide (LCO) are thermal safety risks (Duh et al., 2021), and Lithium Iron Phosphate (LFP) materials are high stability with low energy densities (Saw et al., 2013). Lithium Manganese Oxide (LMO) provides good thermal stability, good voltage, and lower cycling stability (Chen et al., 2024). Nickel Manganese Cobalt Oxide (NMC) is a compromise in capacity, price and rate capability but needs optimization to reduce thermal risks (Li et al., 2019). Nickel Cobalt Aluminum Oxide (NCA) has high energy density but shares safety concerns with NMC(Wittman et al., 2023). Graphite has common application due to its stability and conductivity but the anode capacity is low. Lithium Titanate (LTO) is safe and long-cycle life, and less energy-dense (Sandhya et al., 2014). Silicon/graphite composites enhance capacity, but have cycling stability and volume expansion problems (Beattie et al., 2016).

Table 2: Material composition of different commercial 18650 Li-ion battery

Materials	Key Performance Characteristics
LCO	High energy density and moderate thermal stability (Duh et al., 2021)
LFP	Excellent thermal stability, Good on low-temperature performance (Duh et al., 2021; Zhao et al., 2015)
LMO	Moderate energy density and good thermal stability (Duh et al., 2021)
NMC	High energy density, Moderate thermal stability, Temperature-dependent degradation (Li et al., 2019; Wittman et al., 2023)
NCA	High energy density, Weak temperature dependence in cycle aging, High thermal runaway risk (Li et al., 2019; Wittman et al., 2023)
Graphite	Commonly used anode material, Paired with various cathodes for balanced performance (Beattie et al., 2016)
LTO	Excellent cycle life, Low energy density, Good thermal stability (Sandhya et al., 2014)

4. Impact of Electrode Thickness on 18650 Li-ion Battery Performance:

The 18650 lithium-ion battery performance is dependent on the thickness of the electrodes. Thickening of the electrode will tend to increase energy density and power capacity because they decrease the ratio of inactive materials, hence improving the overall energy density (Geng et al., 2024b). This, however, may result in underutilization of active materials because of the limitation of transport that has a negative effect on rate capability and fast charging performance(Song et al., 2024). Thicker electrodes too are characterized by low rate capability which is mainly because of diffusion limitations and slow diffusion of solid state (Liu & Zhang, 2021). There is also a tendency towards cycling performance degradation with time whereby electrodes with high thickness exhibit more pronounced capacities degradation as a result of mechanical loads and degradation mechanisms (Yu et al., 2023). The thicker electrodes negatively impact the heat characteristics of the battery because thicker electrodes create more heat and hence expand the temperatures and form larger temperature gradients and increase the safety concerns(Zheng et al., 2012). Thicker electrodes are mechanically less tensile-strong and less elastic which makes them more vulnerable to damage and cracking, causes capacity fading faster, and shortens their lifespan.

Table 3: Electrode thickness effect of commercial 18650 Li-ion battery

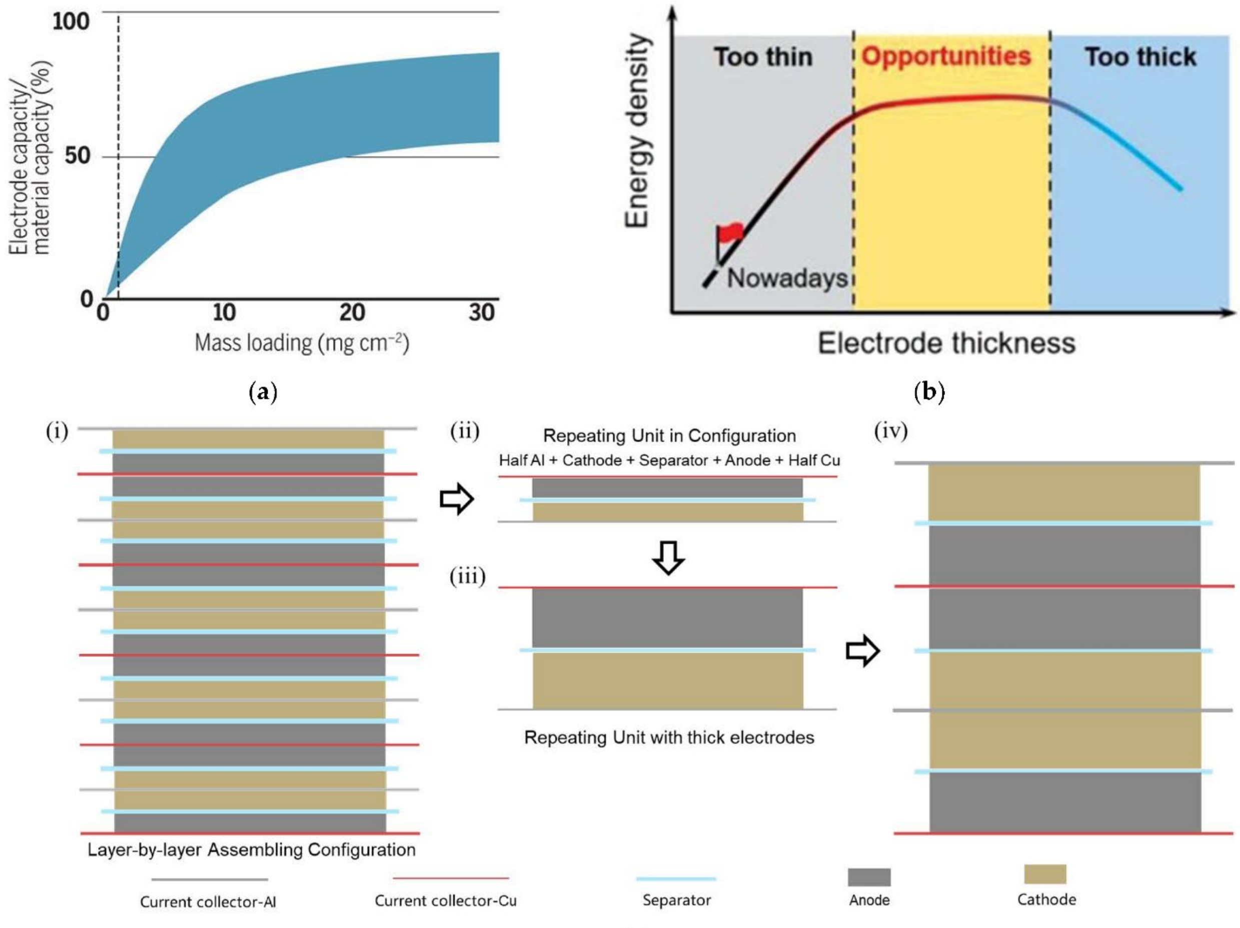
Aspect	Impact of Increased Thickness
Energy Density	Increases due to more active material(Libich et al., 2018)
Rate Capability	Decreases due to poor transport and increased resistance(Xie et al., 2024)
Stability	Decreases with higher capacity fade and heat generation.(Sarawutanukul et al., 2020)
Thermal Behavior	More heat generation and higher temperature rise(Huang et al., 2018)
Mechanical Properties	Lower tensile strength and elastic modulus increased risk of cracking (Blazek et al., 2022)
Optimization	Requires balancing thickness and advanced designs to improve performance (Xu et al., 2019)

5. Impact of Electrode Porosity on Commercial 18650 Li-ion Battery Performance:

Electrode porosity is crucial in determining the electrochemical and thermal performance of 18650 lithium-ion batteries. High porosity enhances ionic transport, reducing internal resistance and improving charge/discharge efficiency, but it can lower volumetric energy density and mechanical stability(Chen et al., 2022). Conversely, low porosity improves structural integrity and capacity retention but may hinder lithium-ion diffusion, leading to higher polarization losses (Sikha et al., 2004). Thermal performance is also affected, as low porosity enhances heat dissipation, preventing overheating, while excessive porosity can cause thermal insulation, increasing safety risks(Hosseinzadeh et al., 2018a). Optimizing electrode porosity through advanced manufacturing techniques, such as controlled pore formation and hierarchical structuring, is essential for balancing energy efficiency, cycle life, and thermal stability in next-generation lithium-ion batteries (Laue et al., 2019).

Table 4: Electrode porosity effect of commercial 18650 Li-ion battery

Aspect	High Porosity	Low Porosity
Charge Efficiency	Enhanced lithium-ion diffusion, reduced stress (Suo et al., 2024)	Increased mechanical stress and potential cracking (Alolaywi et al., 2025)
Cycling Performance	Better at higher porosity (Profatilova et al., 2020)	Lithium deposition reduced performance at high C-rates (Profatilova et al., 2020)
Energy Density	Lower volumetric energy density (Heubner et al., 2019)	Higher volumetric energy density (Alolaywi et al., 2025)
Power Density	Improved ionic transport, higher power density (Alolaywi et al., 2025)	Potential obstruction at high C-rates (Sarawutanukul et al., 2020)
Thermal/Electrical Performance	Optimized with gradient porosity (Hosseinzadeh et al., 2018b)	Better stability and capacity retention (Alolaywi et al., 2025)



(**a**) (**b**)

(**c**)

Figure 3: (a) The electrode capacity has a direct proportion to the active material mass loading of the electrode. (b) Detailed explanation about thick electrode design. (c) Thick electrode design possibilities (Zheng et al., 2023b).

6. Conclusion

This is a review paper that examined the influence of electrode structures on the performance of commercial 18650 lithium-ion batteries in a comprehensive manner. Electrode thickness, porosity and material composition are the main factors that affect the energy density, charge-discharge efficiency, and thermal stability to a considerable extent. These are structural parameters that should be optimized to increase battery performance and longevity. The conclusions are the following:

- Optimization of electrode thickness is necessary with the thicker ones maximizing the energy density at the expense of ion transportation and internal resistance.
- Porosity has a two-fold effect whereby on the one hand, it increases the electrolyte infiltration and ion mobility, but on the other hand, it may decrease the mechanical integrity and the volumetric energy density.
- Battery efficiency is strongly dependent on the choice of materials and NMC, LFP, and NCA cathodes have trade-offs in terms of capacity, thermal stability and cycle life.
- Recent developments in nanostructured materials and methods of fabrication of electrodes give promising avenues of improving lithium-ion battery performance.
- Future studies are suggested to concentrate on new electrode designs like graded porosity, high capacity anode materials to improve the charge/discharge efficiency and cycle stability.

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