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Beyond Active Materials: How the "Inactive Materials" Caps Practical Energy Density in Li-ion Cells

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Abstract. The optimization of inactive materials is critical for enhancing the energy density of lithium-ion batteries, yet it involves complex trade-offs among mechanical, electrochemical, and safety properties. This review looks at five main parts that aren't active in the battery: the current collectors, the separator-electrolyte systems, binders and conductive additives, the layout of how current is collected, and the outer casings of the cells. It points out the main challenges with each one and talks about new ideas and approaches to solve those issues. Thinner current collectors improve energy density but risk mechanical failure and poor adhesion, necessitating surface engineering or structural reinforcements. Separator and electrolyte reductions enhance energy metrics but increase short-circuit risks and impedance, calling for advanced materials with improved stability and wetting. Binders and conductive additives influence both electrical and mechanical performance, where new aqueous binders and nanocarbons offer pathways to higher active material loadings and better electrode integrity. Current collection designs affect resistance and thermal management, with multi-tab and tabless configurations improving uniformity at the cost of manufacturability. Finally, the choice of cell enclosure - pouch, cylindrical, or prismatic - involves balancing volumetric efficiency, structural support, and application-specific requirements. A systems-level approach that co-optimizes these components is essential to achieving higher energy densities without compromising cycle life, safety, or reliability.

Keywords: Lithium-ion Batteries, Inactive Materials, Practical Energy Density, Current Collectors, Separator and Electrolyte

1. Introduction

Lithium-ion batteries are now the primary power source for electric vehicles, portable electronics, and energy storage systems. Research has predominantly focused on active materials, such as those used in the cathode and anode, since these materials are directly responsible for storing and releasing energy. Significant progress has been made in this area, with many studies reporting higher capacities and improved cycle life. However, the specific energy (Wh/kg) achieved at the cell level still lags behind the values reported at the electrode or material level. A major - yet often overlooked - reason for this discrepancy lies in the "inactive materials": the weight and volume contributed by components that do not store charge but are essential for constructing a safe, manufacturable cell.

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The “Inactive Materials” includes current collectors, separator, electrolyte, binders and conductive additives, tabs and leads, and the mechanical enclosure. These components can constitute a large share of a commercial cell’s mass - approaching ~50 wt% in some architectures - which caps the practically achievable specific energy even when active materials continue to improve [1]. Because inactive materials largely set the denominator in specific-energy calculations, reductions achieved at the materials level may translate only partially to the full cell unless the inactive budget is co-optimized [2].

Despite being less discussed than active materials, inactive materials are extremely important for both research and industry. Cell-level energy density directly affects whether a battery can meet the needs of electric vehicles, mobile devices, or large-scale storage. Even slight reductions in inactive materials can produce important benefits when scaled up to battery packs [3]. However, efforts to decrease inactive components often involve trade-offs. For instance, using thinner separators may increase energy density, but it also raises safety concerns - such as an increased risk of internal short circuits resulting from separator damage by electrode protrusions, or thermal runaway due to insufficient thermal stability during battery operation [4]. Using less electrolyte reduces weight but may hurt performance at low temperature. Lighter casings may save mass but decrease mechanical stability, for instance, when the battery is subjected to external collisions during transportation and use, the lighter casing is more prone to deformation or even cracking, which not only damages the internal structure of the battery but also may cause electrolyte leakage, and in severe cases, lead to short circuits or chemical reactions between the electrolyte and external substances, triggering safety accidents. These examples show that optimization of inactive materials requires careful balance rather than simple reduction.

Overall, focusing on inactive materials helps to explain why there is often a gap between material-level energy density and the numbers measured in real cells. By understanding the role of inactive components, future work can bring lithium-ion cells closer to their theoretical limits while keeping them safe and reliable.

Specifically, this paper pursues five objectives: (i) Current collectors (Al/Cu): characterise the thinness–adhesion–reliability triad and evaluate measures such as surface texturing/coatings, double-sided coating, and edge reinforcement; (ii) Separator and electrolyte: delineate workable windows for thin separators and electrolyte-to-capacity ratios, highlighting low-temperature performance, puncture risk, and pack-level uniformity; (iii) Binders, conductive additives, and solid volume fraction: map the ranges that retain electrode mechanical integrity while preserving active-material volume, comparing PVDF and SBR/CMC systems and carbon variants; (iv) Tabs and interconnects: compare single, multiple and tab-less layouts in terms of resistive losses, thermal hotspots, manufacturability, and vibration robustness, clarifying when ‘less metal’ is counter-productive; and (v) Enclosure and form factor: contrast cylindrical, prismatic and pouch formats in how enclosure mass, mechanical support and thermal pathways constrain or enable cell-level Wh/kg with guidance on when each format is advantageous.

2. Literature review

While new materials like high-nickel layered oxides and silicon-based anodes promise big improvements in battery energy capacity, the actual amount of energy these batteries can store in real life is mostly limited by their inactive parts. These non-active components don't take part in the energy reactions, but they play a essential role - they hold the battery's structure, help ions and electrons move smoothly, and keep the battery safe during use. In this section, we'll look at five

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main types of inactive materials, and talk about the advantages and disadvantages of each, and give some solutions to make batteries to get better performance.

2.1. Current collectors : the thickness-adhesion-reliability triad

Current collectors, typically aluminum for the cathode and copper for the anode, contribute significantly to battery weight due to their density. Making these foils thinner can enhance volumetric energy storage, but excessively thin layers may struggle to stick properly and maintain long-term strength.

Foils that are too thin - typically below 8 μm for copper and 10 μm for aluminum - may create issues during electrode coating and cell assembly processes [5]. They make handling more difficult and can lead to wrinkles or even cracks. More importantly, these ultra-thin foils tend to stick less firmly to the electrode coatings. When the battery charges and discharges repeatedly, the active materials inside expand and contract, which puts stress on the coating. Over time, this can cause the coating to peel away, leading to a loss of capacity and higher resistance in the cell [6].

Innovative countermeasures are emerging. Surface patterning techniques increase specific surface area, offering improved anchor sites for slurry binding and substantially boosting adhesion - all without weight penalty [7]. Specialty coatings can be applied to enhance corrosion resistance and interfacial durability, while also conferring a modest improvement in binding strength [8]. Dual-sided coating is an efficient production strategy that effectively halves the foil mass per unit capacity; however, it imposes stringent demands on foil homogeneity and tension control. Another approach involves selectively reinforced edges: localized thickening or protective coatings along the foil periphery help avert tearing - a critical flaw in cylindrical and prismatic cell winding - while preserving overall thinness across the electroactive region [9].

2.2. Separator and electrolyte: defining workable windows

Since the main role of the electrolyte is to move ions around, finding the right balance when improving separators and electrolytes is really important. You want materials that work well, store enough energy, and stay safe all at once.

Separators today, made from materials like polyethylene (PE) or polypropylene (PP), typically range in thickness from about 7 to 12 micrometers. Making separators thinner allows more space for active materials and shortens the path ions need to travel, which can boost the battery's power. However, this also increases the risk of things like electrode particles, lithium dendrites, or tiny contaminants piercing through, which can lead to internal short circuits [10]. Plus, thinner membranes often aren’t as strong mechanically and don’t handle heat changes very well, which can be dangerous if the battery is abused. That’s why finding an optimal thickness is important - what works for small electronics might not be safe enough for cars.

The quantity of electrolyte employed, expressed as the electrolyte-to-capacity (E/C) ratio, also plays a critical role. Reducing electrolyte volume can enhance energy density; however, an insufficient amount may result in inadequate pore wetting, increased resistance, and accelerated performance degradation - particularly under cold conditions where the electrolyte viscosity rises [11]. This results in lower power output and can cut short charging sessions. On larger battery packs, differences in E/C ratios among individual cells can lead to uneven charge and health, limiting overall capacity. To meet the demands of next-generation batteries, electrolyte formulations with better wetting and temperature performance are essential, enabling even lower E/C ratios without sacrificing cell performance [12].

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2.3. Binders, conductive additives, and solid volume fraction

The electrode matrix, composed of binders and conductive additives, determines both the electrochemical performance and mechanical resilience of the coating.

Binder systems often use different types of binders to hold electrode materials together. Traditional polyvinylidene fluoride (PVDF) binders are known for their durability in electrochemical applications, but they require using harmful solvents like NMP during processing. Plus, PVDF usually provides only decent adhesion, meaning more binder (around 3-5 wt%) is often needed. On the other hand, water-based alternatives - such as combining styrene-butadiene rubber (SBR) with carboxymethyl cellulose (CMC) - offer stronger binding, cost less, and are more environmentally friendly. This makes it possible to use less binder overall, which in turn increases the amount of active material in the electrode [13]. However, SBR/CMC systems tend to underperform when used with high-voltage cells. The choice of binder usually depends on the active material: for silicon anodes, which expand and contract greatly during charge and discharge cycles, more advanced aqueous binders or innovative polymer designs are usually necessary to keep everything intact and working well [14].

Conductive additives like carbon black have long been the go-to for creating conductive networks in electrodes. However, because it has such a large surface area, it can cause electrolyte breakdown and lead to too much SEI formation, which isn't ideal. Recently, newer carbon materials like carbon nanotubes (CNTs) and graphene are showing promise - they can deliver similar or better electrical conductivity even at lower amounts. Plus, their unique shapes, whether fibrous or flat, can help reinforce the electrode structure, making it more durable and flexible. This added mechanical strength helps prevent cracks and improves overall stability [15].

The overarching goal is to map the parameter space of binder content, additive type, and solid loading to achieve electrodes that are both mechanically robust and electrochemically optimal.

2.4. Tabs and interconnects: architecture of current flow

The architecture of current collection - from the electrode sheet to the external terminals - constitutes a pivotal yet frequently underestimated dimension of cell design. Choosing between single-tab, multi-tab, or no-tab setups really matters when it comes to how well things perform and how long they last.

Resistive losses and temperature variations become more major in single-tab designs. These layouts are simpler to produce but cause electrons to travel longer distances, especially in larger cells. This increases the resistance within the cell, leading to hotspots near the tabs, which can speed up degradation and raise safety issues. Using multi-tab configurations helps reduce the length electrons need to travel, lowering internal resistance and improving both the cell's ability to handle high rates and its temperature uniformity [16]. Tab-less designs push the idea even further by cutting down almost all the transverse electrical resistance.

Manufacturability and mechanical strength often involve some trade-offs, especially when dealing with complex designs. Every tab needs to be welded carefully, which adds extra steps to the process and can create potential points where things might go wrong. Especially in automotive applications, vibrations are a big concern - if the welds aren't strong enough, they can loosen over time. This can lead to increased resistance or even system failures. Pursuing minimal metal use within current collectors can prove misguided if interconnect current density escalates, provoking excessive Joule heating. Hence, the optimal configuration is seldom defined solely by metal

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minimization, but rather by achieving maximal current collection efficiency and reliability tailored to specific cell formats and operational demands [17].

2.5. Enclosure and form factor: final packaging solution

The cell enclosure is the heaviest single component that is not active, and its design closely relates to the shape and size of the cell itself.

Cylindrical cells, which use steel or aluminum shells, are known for their strong mechanical durability, providing rigidity and making it easier to build modular battery packs. However, this advantage comes with a major increase in weight. Also, their shape means they don't pack together as tightly as possible within the battery modules, which can reduce the overall energy stored in the pack. Managing heat effectively also requires careful engineering to ensure good contact and to minimize gaps between the cells [18].

Prismatic cells are usually housed in sturdy aluminum cases. They make better use of space compared to cylindrical cells and have flat surfaces that make attaching cooling systems easier. Still, their heavier casings add to the overall weight, and dealing with increased internal pressure over time needs built-in venting features.

Pouch cells use thin, lightweight laminated foil packaging instead of rigid metal shells. This design helps achieve lighter weight and better volume usage for each cell. Their flexible structure allows the electrodes to be compressed easily with minimal external pressure. On the downside, pouch cells are less mechanically stable, so they need strong support within the module, and they are more prone to swelling, gas buildup, and damage if overheated [19].

Choosing the right cell type always depends on the specific application: pouch cells are ideal when weight and space are critical and good structural support can be provided; cylindrical cells suit applications that need reliable, easy-to-manufacture solutions that have been proven over time; and prismatic cells are often preferred in electric vehicles because they strike a balance between energy density, space efficiency, and ease of integration. To improve overall battery performance, optimizing the inactive materials - those parts of the cell that aren't involved in energy storage - is key. Each of the five primary types of non-active components brings advantages and potential challenges. Finding the right balance requires thoughtful evaluation of various factors to ensure optimal performance and efficiency.

2.6. Result & discussion

Current collectors (usually made from aluminium and copper foils) are a major focus area when it comes to making batteries lighter because they are quite heavy. Using thinner foils can increase how much energy the battery can store but there are also downsides. Thinner materials are less strong so they are harder to handle. They can wrinkle more or break when being handled during manufacturing and might not stick as well to the electrode coatings. This can cause the active materials to peel off and the battery to fail faster over its lifetime. Researchers are therefore finding clever solutions such as designing patterns on the surface, special coatings to improve the interfaces, coating both sides of the foil and reinforcing the edges locally to allow us to use super thin foils without them breaking. The requirements for the separator and the electrolyte system are a fine balance between performance, energy density and safety.

Thinner separators also shorten the distance over which ions must transport and liberate space for active materials, which can improve both the gravimetric and volumetric energy densities. However, they also become more likely to be penetrated by debris or lithium dendrites and show a reduced

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thermal stability. Similarly, a reduction of the electrolyte-to-capacity ratio (E/C) improves the energy density but may decrease the ionic conductivity, particularly at low temperatures, and lead to cell-to-cell variations within a pack.

Superior electrolytes with improved wetting and electrochemical stability as well as operation over a broader temperature range are necessary to enable lower E/C ratios without performance impacts. In the electrode, binders and conductive additives hold everything together mechanically and impact on the electrical performance.

The separator and electrolyte system require a delicate balance among performance, energy density, and safety. Thinner separators shorten ion transport distances and free up space for active materials, thereby improving both gravimetric and volumetric energy densities. However, they also become more prone to penetration by debris or lithium dendrites and exhibit reduced thermal stability. Similarly, lowering the electrolyte-to-capacity (E/C) ratio can enhance energy density but may compromise ionic conductivity, especially under cold conditions , and lead to cell-to-cell variations within a pack. Advanced electrolytes that improve wetting and perform across a wider temperature range are essential to enabling lower E/C ratios without sacrificing performance.

Inside the electrode, binders and conductive additives play a critical role in holding everything together physically and ensuring the electrical performance is maintained properly. While PVDF is still a popular binder, water-based options like SBR/CMC are gaining popularity because they provide stronger sticking power and are better for the environment. They also allow for higher amounts of active materials to be used, but they don’t quite hold up as well under high voltages. Conductive additives like carbon black help electrons move more easily, but they can sometimes cause unwanted reactions and lead to the growth of the solid electrolyte interphase (SEI). Recently, materials such as carbon nanotubes (CNTs) and graphene have shown promise because they conduct electricity better at lower amounts and can also help strengthen the electrode structure, making it less likely to crack. However, using these advanced materials requires careful tweaking to avoid potential issues that could hurt performance.

How the current collection system is designed plays a large role in how the current gets around, how much resistance is in the way, and where the heat collects. Using a single tab in manufacturing can make the process easier, but it might lead to uneven current flow and hot spots. Designs with multiple tabs or no tabs allow the electrons to travel a shorter distance, with less resistance and more even temperatures. They’re generally more complicated to produce and can sometimes have issues with weld fractures when they vibrate. Creating effective collection systems means designing solutions that are reliable, long-lasting, and customized to the specific type of cell and its intended use. Like any other decision in battery design, choosing the right cell enclosure and shape involves trade-offs between weight and strength, and how easily you want to embed the battery into the final product.

Pouch cells, consisting of lightweight laminated films, offer high energy density, but they need some kind of support to keep them flat.Rigid metal cylindrical cells offer great protection and durability, but they’re not very space-efficient. Prismatic cells fall in between. They’re often preferred in automotive applications because they offer a balance of good energy capacity, easy modularity, and adequate structural properties. But the best choice depends on what’s most important to you - whether it’s light weight, maximizing space, safety, or manufacturing simplicity. Figure 1 shows Schematic of a lithium-ion battery. Shown are the active materials and inactive parts, current collectors, separators, electrolytes, and coatings on the electrode lamellas.

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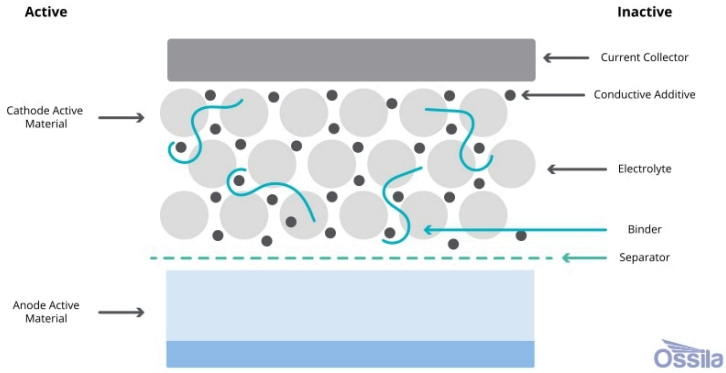

Figure 1. Schematic structure of a lithium-ion battery [20]

3. Conclusion

So, in summary this review, how much energy a Li-ion battery can hold is not simply a function of the active materials in the cell, but just as much how much energy depends on the weight and space of parts that are not involved in storing energy.

Current collectors need to be thin enough to save weight, but also strong enough to hold everything else together. Researchers are working on more clever surface treatments to make these current collectors and better design approaches are being developed. The separator and electrolyte formulas must be finely tuned to get the right balance between energy capacity, safety, and consistent performance at different temperatures.

Binders and conductive additives are two different things, but both play important roles in providing mechanical stability to the battery and helping the current to flow more efficiently. Exciting recent advancements have been made in using water-based binders combined with ultra-thin nanocarbon materials.How we design the current collector, the tabs and connecting parts, can affect how the current is distributed and how the heat flows, and how the whole thing works together.

Future work should concentrate on developing multifunctional materials, new cell configurations, and personalized designs to enhance the energy capacity without compromising safety and lifetime. A systems-level perspective is essential if we want to truly use the full capabilities of Li-ion batteries and meet the demanding needs of practical applications.

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