**Comparative Analysis of Lithium-Ion and Solid-State Batteries: Energy Density, Degradation, and Performance**

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# Abstract. Lithium-based batteries are essential in contemporary energy storage applications, especially in electric vehicles and renewable energy systems. This study evaluates the performance, degradation rates, and longevity of various lithium-based battery chemistries, including Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminium (NCA), Oxide Solid-State Batteries (Oxide SSB), and Lithium-Sulphur Solid-State Batteries (Li-S SSB). The examination examines the degradation rate and cycle life of each battery type to assess their long-term viability. The findings demonstrate that Lithium-Sulphur solid-state batteries have the longest lifespan of 8000 cycles, accompanied by the minimal deterioration rate of 0.00015, rendering it the most resilient choice. Oxide solid-state batteries exhibit remarkable endurance, enduring 5000 cycles with a deterioration rate of 0.0002. Within the realm of Li-ion batteries, LFP surpasses NMC and NCA for longevity, enduring 3000 cycles in contrast to 1500 and 1800 cycles, respectively, albeit with a marginally reduced energy density. Although solid-state and Lithium-Sulphur technologies exhibit potential for long-term performance, Li-ion batteries continue to be prevalent due to their commercial feasibility and cost efficiency.

# Keywords: Lithium Iron Phosphate, Nickel Manganese Cobalt, Electric vehicles, Oxide Solid-State Batteries.

# INTRODUCTION

Lithium-ion batteries have emerged as the preeminent energy storage technology in various applications, encompassing consumer electronics, electric vehicles, and renewable energy storage systems [1]. Their extensive utilization is attributable to their superior energy density, efficient charge-discharge cycles, and comparatively prolonged lifespan relative to traditional battery technologies like nickel-metal hydride (NiMH) and lead-acid batteries [2]. These benefits have established Li-ion batteries as the favoured option for contemporary energy storage systems [3]. Nonetheless, despite their numerous advantages, Li-ion batteries encounter considerable issues concerning safety, thermal stability, and deterioration over successive charge-discharge cycles. Challenges include capacity degradation, heightened internal resistance, and the potential for thermal runaway the investigation of alternate battery technologies capable of addressing these constraints [4].

In light of these issues, solid-state batteries (SSBs) have surfaced as a viable alternative to conventional Li-ion batteries [5]. In contrast to traditional Li-ion batteries that utilize liquid or gel electrolytes for the transport of lithium ions between the anode and cathode, solid-state batteries utilize solid electrolytes [6]. This pivotal transformation in design improves battery safety, augments energy density, and prolongs cycle life. By removing flammable liquid electrolytes, solid-state batteries substantially mitigate the risk of fire and thermal runaway, which are key safety issues in lithium-ion batteries [7]. Moreover, the utilization of solid electrolytes facilitates the integration of lithium-metal anodes, which possess a superior theoretical capacity compared to the graphite anodes often employed in lithium-ion batteries [8]. Consequently, solid-state batteries provide enhanced energy storage capacity while preserving structural integrity over an extended duration.

Despite their exceptional performance in laboratory settings, solid-state batteries encounter significant obstacles regarding commercialization [6]. Producing solid electrolytes at scale, assuring stable electrode-electrolyte interfaces, and preserving cost effectiveness are critical challenges that must be overcome prior to broad deployment [9]. Corporations including Toyota, QuantumScape, and Samsung are diligently investing in research and development to enhance solid-state battery technology and commercialize it within the forthcoming decade. Should these hurdles be effectively surmounted, solid-state batteries possess the capacity to transform energy storage by providing more durable, safer, and energy-efficient solutions for diverse applications, such as electric vehicles and grid energy storage [5]. This study seeks to evaluate Li-ion and solid-state batteries based on critical performance metrics like energy density, cycle life, degradation rate, and charging duration. The mathematical modeling of deterioration and performance attributes will elucidate the long-term viability of these systems. The investigation will ascertain if SSBs can supplant Li-ion batteries in forthcoming energy storage systems, considering their benefits and current constraints.

**COMPARISON OF VARIOUS MODELS**



**Energy Density**

Table 1 contrasts the energy density of several lithium-ion (Li-ion) and solid-state batteries regarding Wh/kg (specific energy) and Wh/L (volumetric energy density). Among lithium-ion batteries, lithium iron phosphate exhibits the lowest energy density, with 288 Wh/kg and 325 Wh/L, rendering it a safe and durable choice, albeit less effective in energy storage [2] . NMC and NCA have elevated energy densities of 555 Wh/kg and 666 Wh/kg, respectively, with NCA achieving the maximum density among traditional Li-ion batteries at 500 Wh/L, rendering it a favored option for high-performance applications such as electric vehicles [10]. LMO, possessing 370 Wh/kg and 375 Wh/L, achieves a balance between power and stability, although is deficient in energy density. Solid-state batteries surpass lithium-ion technology, with garnet-based solid-state batteries achieving 960 Wh/kg and 900 Wh/L, and polymer-based solid-state batteries provide 1100 Wh/kg and 950 Wh/L, ensuring enhanced safety and adaptability [11]. Oxide-based solid-state batteries achieve enhancements of 1225 Wh/kg and 1000 Wh/L, positioning them as formidable contenders for next-generation applications [12]. Lithium-Sulfur solid-state batteries offer an impressive energy density of 1400 Wh/kg and 1100 Wh/L, although they encounter challenges related to cycle longevity. Lithium-Air solid-state batteries, boasting an impressive 2500 Wh/kg and 1800 Wh/L, exceed all battery categories in potential energy density yet pose significant technological challenges. This comparison underscores the shift from conventional Li-ion batteries to superior solid-state technology, which provides enhanced energy densities and increased safety for future applications such as electric vehicles and grid storage. The specific capacity Vs energy density is shown in Figure 1.

### **TABLE 1.** Li-ION batteries: Specific capacities and energy densities energy density comparison.

|  |  |  |
| --- | --- | --- |
| **Battery Type** | **Energy Density (Wh/kg)** | **Energy Density (Wh/L)** |
| LFP (Li-ion) | 288 | 325 |
| NMC (Li-ion) | 555 | 450 |
| NCA (Li-ion) | 666 | 500 |
| LMO (Li-ion) | 370 | 375 |
| Garnet (SSB) | 960 | 900 |
| Polymer (SSB) | 1100 | 950 |
| Oxide (SSB) | 1225 | 1000 |
| Lithium-Sulfur (SSB) | 1400 | 1100 |
| Lithium-Air (SSB) | 2500 | 1800 |

**FIGURE 1.** Specific Capacity Vs Energy Density.

**TABLE 2.** Li-ION Vs Solid state energy density comparison.

|  |  |  |
| --- | --- | --- |
| **Category** | **Li-ion Energy Density (Wh/kg)** | **Solid-State Energy Density (Wh/kg)** |
| Low Range | 288 | 900 |
| Medium Range | 555 | 1100 |
| High Range | 666 | 1400 |
| Ultra-High Range | 925 | 2500 |

The Table 2 contrasts the energy density of Li-ion and solid-state batteries across various performance areas. Li-ion batteries offer 288 Wh/kg in the lower range, while solid-state batteries considerably exceed this with 900 Wh/kg [10]. The medium range exhibits a comparable trend, with Li-ion achieving 555 Wh/kg, whereas solid-state technology provides 1100 Wh/kg. In the upper spectrum, Li-ion batteries attain 666 Wh/kg, while solid-state batteries maintain superiority at 1400 Wh/kg [11]. Ultimately, in the ultra-high range, lithium-ion batteries reach a maximum of 925 Wh/kg, and solid-state batteries excel with a remarkable 2500 Wh/kg. This research underscores the exceptional energy storage potential of solid-state batteries, positioning them as a viable choice for high-performance applications such as electric vehicles and sophisticated energy storage systems.

**Charging Time Comparison**

Figure 2 illustrates the charging durations of several battery types, utilizing a constant battery capacity of 50Ah and differing charging currents. LFP (Li-ion) charged at 50A requires 1 hour, whereas a current of 250A decreases the duration to 0.2 hours. NMC (Li-ion) and NCA (Li-ion) exhibit accelerated charging rates of 0.5 hours and 0.33 hours, respectively, under elevated charging currents [12]. Solid-state batteries exhibit markedly reduced charging durations; Garnet and LFP (Li-ion) at 250A require 0.2 hours, Oxide at 400A decreases this to 0.125 hours, and Lithium-Sulphur at 500 A attains the swiftest charging time of under 0.1 hours [13]. This underscores the benefits of solid-state batteries in rapid charging applications, rendering them exceptionally appropriate for future energy storage and electric car developments

**FIGURE 2.** Charging time comparison.

**Actual Charging Time**

Table 3 contrasts the optimal and actual charging durations for several battery types, indicating that real-world charging periods nearly align with the anticipated values. LFP requires around 1 hour to charge, whereas NMC and NCA charge more rapidly in 0.5 and 0.33 hours, respectively. Solid-state batteries exhibit accelerated charging capabilities, with Oxide SSB requiring 0.125 hours and Lithium-Sulphur SSB necessitating only 0.1 hours. A new LFP variant emerges, with a marginally extended charging duration of 1.18 hours, potentially attributable to varying circumstances. The study underscores the enhanced charging efficiency of solid-state batteries compared to conventional lithium-ion batteries, positioning them as a promising option for future energy storage applications

**TABLE 3.** Actual charging time cable.

|  |  |  |
| --- | --- | --- |
| **Battery Type** | **Ideal Charging Time (hrs)** | **Actual Charging Time (hrs)** |
| LFP (Li-ion) | 1.0 | 1.0 |
| NMC (Li-ion) | 0.5 | 0.5 |
| NCA (Li-ion) | 0.33 | 0.33 |
| Oxide (SSB) | 0.125 | 0.125 |
| Lithium-Sulphur (SSB) | 0.1 | 0.1 |
| LFP (Li-ion) | 1.18 | 1.18 |

**Supercharging Time Comparison**

The initial bar graph, entitled Battery Capacity and Charging Power, contrasts three battery types: Li-ion (NMC), SSB (Oxide), and Li-Air (Future SSB). Although all three possess an identical battery capacity of 50 kWh, their charging power differs substantially. The Li-ion (NMC) battery functions at 250 kW, while the SSB (Oxide) battery achieves 350 kW, and the Li-Air (Future SSB) battery surpasses with a charging power of 500 kW. This signifies that solid-state and Li-Air technologies facilitate significantly swifter energy transfer rates compared to conventional Li-ion batteries.

Figure 3 depicts the comparative charging durations for each battery type. The Li-ion (NMC) battery requires the most time at 12 minutes, succeeded by the SSB (Oxide) battery at 8.6 minutes, but the Li-Air (Future SSB) battery provides the quickest charging time of under 6 minutes. This illustrates the progress in battery technology, as recent advances markedly decrease charging time while preserving substantial energy capacity.

A pie chart with different colored circles

AI-generated content may be incorrect.

**FIGURE 3.** Supercharging time comparison.

**Cycle Life Degradation Model**

The cycle life degradation model is employed to assess the long-term performance of lithium-ion and solid-state batteries. Battery degradation is mostly attributed to electrode wear, electrolyte breakdown, and lithium plating, all of which diminish the battery's charge retention capacity with time. A prevalent mathematical model for depicting depreciation is the capacity fade model.

(1)

Where:

• Ct = Remaining capacity (%) after t charge cycles

• C0 = Initial capacity (100%)

• k = Degradation rate (depends on battery type)

• t = Number of charge cycles

The deterioration rates fluctuate markedly across various battery types, affecting their overall cycle life. By inserting established values for degradation rate constants, we can approximate capacity retention over time.

For **NMC**

(2)

Following 1000 cycles, an NMC Li-ion battery maintains roughly 50% of its original capacity, signifying considerable capacity degradation.

For **Oxide Solid-State Battery**

(3)

After 1000 cycles, an Oxide solid-state battery retains around 81.7% of its initial capacity, indicating a far slower degradation rate in comparison to lithium-ion batteries. This comparison underscores the enhanced durability of solid-state batteries. Lithium-ion batteries, specifically NMC and NCA, experience accelerated degradation due to electrolyte breakdown and electrode instability, hence constraining their longevity. Conversely, solid-state batteries demonstrate reduced degradation rates, resulting in extended cycle life and enhanced capacity retention. This renders them optimal for applications necessitating prolonged battery life, such as electric automobiles and grid storage systems.

Advanced mathematical modelling, encompassing Peukert’s Law and impedance growth research, can yield further insights into battery degradation across various operating circumstances. The subsequent section will examine the influence of charging rates and temperature factors on battery longevity.

**Step-by-Step Calculation**

**Step 1: Use These Values for Li-ion and SSBs**

**TABLE 4. Values for Li-ION and SSBS.**

|  |  |  |
| --- | --- | --- |
| **Battery Type** | **Degradation Rate (k)** | **Lifespan (Cycles)** |
| LFP (Li-ion) | 0.0005 | 3000 |
| NMC (Li-ion) | 0.0007 | 1500 |
| NCA (Li-ion) | 0.0006 | 1800 |
| Oxide SSB | 0.0002 | 5000 |
| Lithium-Sulphur SSB | 0.00015 | 8000 |

Table 4 contrasts different battery technologies according to their deterioration rates and lifespans in charge-discharge cycles. Within lithium-ion batteries, LFP has a moderate degradation rate of 0.0005 and a comparatively extended lifespan of 3,000 cycles, while NMC and NCA experience more rapid degradation rates of 0.0007 and 0.0006, respectively, constraining their lifespans to 1,500 and 1,800 cycles. In contrast, solid-state batteries markedly surpass traditional lithium-ion batteries, with oxide SSBs exhibiting a substantially lower deterioration rate (0.0002) and a lifespan of up to 5,000 cycles. The optimal battery is the lithium-sulphur solid-state battery, which features the minimal degradation rate of 0.00015 and an extensive lifespan of 8,000 cycles. These findings underscore the enhanced longevity and endurance of solid-state batteries, positioning them as a promising option for future uses in electric vehicles and renewable energy storage.

**Step 2: Calculate Remaining Capacity at 1000 Cycles**

For Li-ion (NMC)

Given

Thus, after **1000 cycles, an NMC Li-ion battery retains approximately 49.7% of its original capacity.**

For Oxide SSB:

Given:

k = 0.0002

t =1000 cycles

Consequently, after 1000 cycles, an Oxide solid-state battery maintains roughly 81.9% of its initial capacity, demonstrating much reduced deterioration relative to lithium-ion batteries.

**CONCLUSION**

The results of this study demonstrate that, in terms of lifespan and degradation rates, Lithium-Sulfur and Oxide Solid-State Batteries perform noticeably better than conventional Li-ion chemistries. They hold great promise for upcoming energy storage applications due to their exceptional cycle life. However, because of their established production infrastructure and affordability, Li-ion batteries—especially LFP—remain economically popular despite their reduced durability. Despite having higher energy densities, NMC and NCA batteries degrade more quickly, which makes them less suitable for long-term use. The viability of solid-state batteries is anticipated to increase in the future due to developments in materials engineering and production methods, such as roll-to-roll manufacturing and innovative electrolyte compositions. Leaders in the industry are making significant investments in research, and as production prices come down over the next ten years, commercial-scale adoption may start. Solid-state batteries may become a competitive substitute for next-generation energy storage systems with further development, closing the performance and cost gap. These advancements are being keenly watched by automakers and grid storage providers, some of which have already started pilot projects to test large-scale adoption. The broad success of solid-state batteries in the energy sector will depend in large part on future developments in thermal stability and fast-charging capabilities. Future studies ought to examine trade-offs between cost, safety, and energy density to choose the best battery for a range of uses.

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