An Analysis on Lithium-Ion Batteries and Their Future Trajectory for Serving Humanity

Xucheng Pei
Nanjing Tech University Pujiang Institue, Nanjing, 211222, China

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Abstract: The world is facing a significant challenge with climate change, necessitating the search for energy sources that minimize harm to our planet. Harnessing clean energy from the sun, wind, and water is essential, but effective energy storage solutions are equally vital. Lithium-ion batteries excel in this regard, offering high energy density in a compact form and proven reliability. Current research delves into the manufacturing methods and working mechanisms of batteries for high energy density and cycle life. However, these advancements come with safety and environmental concerns that must be addressed. The push for higher energy densities is driving the development of new technologies, facing hurdles such as cycle performance and stability issues. Safety, particularly the risk of thermal runaway, remains a critical concern, emphasizing the need for safer battery chemistries and designs. Improper disposal of batteries underscores the necessity for sustainable manufacturing and recycling practices. The industry must strike a balance between increasing energy density and ensuring safety and sustainability. Innovation in materials and technologies, such as silicon anodes, lithium-rich cathodes, and high-voltage $LiCoO_2$, is expected to bring a significant increase in energy density. A shift towards using aqueous electrolytes may also reduce the environmental impact. Researchers, industry experts, and regulatory authorities must work in unison to develop strategies that maximize efficiency, ensure safety, and promote sustainability. The combination of technological innovation, environmental stewardship, and safety considerations is what will drive the future of lithium-ion batteries. A focused drive toward these goals holds much promise for serving humanity's energy needs while contributing to a cleaner and more sustainable future.

1 INTRODUCTION

In the dynamic current global climate crisis, countries all over the world are advocating for more emphasis on sustainable development. It is considered that hydropower, wind power, and solar power are the primary three forms of clean energy. Energy storage for this vast amount of clean energy represents a massive need. Lithium-ion batteries might be the best solution to date. It is developed and perfected in an energy-dense (230 Wh/kg), highly reliable, and long cycle life battery for many years applied to the market a variety of uses.

Now, there is an upsurge of interest in improving these batteries. In addition to the omnipresent lithium-ion batteries used in every other device, various innovative lithium-ion technologies are being introduced in research groups. Aqueous batteries are named as safe but, at the same time, not yet a convincing alternative to replace a traditional lithium-ion battery in performance. The research on solid-state batteries is still early and has yet to convince the industry. Although lithium-sulfur, and lithium-air batteries have shown exceptionally high theoretical energy densities, at least in practice, they have not reached those levels.

The aim of this paper is to gently introduce new entrants to the field in a straightforward and accessible fashion, with one goal: to shine some light on possible future development in the generation of lithium-ion batteries.

2 STATUS QUO

2.1 Cathode

The common lithium-ion batteries used in phones and tablets are NMC, LFP, and NCA batteries, with organic electrolytes. Current types of lithium-ion batteries include single transition metal oxide batteries, high voltage ones, and high-capacity ones

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(Kim et al., 2019). Many of cathode materials are composed of metals such as Li, Ni, Mn and Co in varying concentrations.

2.1.1 Single Transition Metal Oxide Batteries

These batteries are super popular because they have a lot of energy packed into them, and they don't lose their charge quickly. People often call them LCO batteries because they're made with $LiCoO_2$. It's like they've got all the power and none of the hassle (Kim et al., 2019). LCO batteries have a layered structure that allows lithium ions to move easily, enabling high energy storage capacity. Due to the geographic concentration of cobalt reserves in DRC, combined with political instability and supply chain risks, the industry is exploring alternatives. These alternatives include cathode materials with less cobalt or none at all, like lithium nickel manganese oxide (LNMO) etc.

2.1.2 Mixed Transition Metal Oxide Batteries

These batteries aim to increase energy density by raising the operating voltage of the battery. High-voltage cathode materials and compatible electrolytes are used to achieve this. However, challenges remain in ensuring the stability and safety of the electrolyte. This kind of cathode is like a cocktail. It's made up of Mn, Co, and Ni, therefore this type of cathode is also called NMC cathode. In other words, NMC is a layered material made of Cobalt (Co), manganese (Mn), and nickel (Ni) in different proportions. It offers low internal resistance, high stability, and high specific capacity, in that order. So far, types of NMC cathodes include NMC111, NMC442, NMC523, NMC622, and NMC811. NMC811 has more nickel, giving it higher capacity but also raising stability and safety concerns due to nickel's reactivity with the battery's electrolyte (Murdock et al., 2021). The sustainability of NMC cathodes is also challenged by cobalt's high cost and supply issues due to social and environmental problems of Congo.

2.1.3 Spinel and Olivine Cathodes

Spinel and olivine cathodes are spinel $LiMn_2O_4$(LMO) and olivine $LiFePO_4$ respectively. The spinel that has been studied the most and entered the EV market is LMO. However, the short lifetime, low energy density, and low capacity of LMO limit its usage. One major fault about LMO is an asymmetric lattice distortion which can be ascribed to the Jahn-Teller effect (Kim et al., 2019).

$LiFePO_4$ (LFP) is an olivine-structured cathode that has a high level of thermal and electrochemical stability along with a great cycle life. These characteristics, together with the fact that it uses naturally plentiful iron and is inexpensive, make it a desirable cathode alternative for a variety of battery applications. For olivine $LiFePO_4$ as cathode, the major virtue is its stability, preventing some oxygen loss during charge cycles. Surely, there's also a risk of capacity loss, the cause of this is due to the low Li^+ diffusion and electronic conductivity.

2.2 Anode

Currently, most LIBs use graphite as their anode. Graphite has relatively low cost, a high capacity, a low operating potential, and excellent cycling stability (Li et al., 2022). But it has a series of problems like mechanical cracks, electrolyte side reaction, making make it have more to be desired. It is imperative that researchers and business leaders take action and establish new benchmarks for high energy density lithium-ion batteries. At the moment, these batteries with standard carbon anodes and lithium metal oxide cathodes have about the best energy density available.

3 CURRENT DEFECTS

3.1 Safety Concerns

Because Li-ion cells have higher energy densities than conventional non-rechargeable batteries and because they also contain toxic and flammable electrolytes, there are a number of extra safety problems that need to be carefully addressed.

3.1.1 Thermal Runaway

Thermal runaway occurs when the heat generation within a battery cannot be controlled for high temperature. It's often triggered by mechanical, electrical, and thermal and electrochemical abuse (Huang et al., 2021). Mechanical abuse is often triggered by traffic accidents, like a penetration or crash of the battery. The main cause of damage is that the separators of the battery are ruptured, hence an internal short circuit. Inappropriate operations of battery like overcharging and over-discharging can be considered as electrical abuse. If a battery is charged at a current which is too much, the lithium ions will accumulate on the anode and stay active, leading to a thermal runaway. Thermal abuse is the rapid or high temperature rise during charging and discharging. It ’s easier to happen as the batteries age (Huang et al., 2021). Electrochemical abuse is a relative new concept (Bubbico et al., 2018). Electrochemical abuse refers to situations where the battery is subjected to operation outside of its designed parameters, causing stress beyond a battery’s normal operating limits.

3.1.2 Environmental Hazard

So far, the electrolytes applied by lithium-ion batteries are organic ones. One point with organic electrolytes is that they are highly flammable which is irritating to skin, eyes and mucous membranes. When batteries are disposed of without any pretreatment, the heavy metals in them may not be harmful on their own, but when they combine with organic molecules, they may seep into the ground's layers and contaminate the water table and soil. It is possible for the hazardous substances to seep into the ground and water, endangering people through direct or indirect contact. If an electrical vehicle catches fire in a traffic accident, it will also release highly toxic, flammable gases, vapours, and smoke. Traditional electrolytes are manufactured using harmful chemicals such as lead, cadmium. Dimethyl carbonate (DMC), EMC (ethyl methyl carbonate) and DEC (diethyl carbonate) are commonly used as electrolyte materials (Hess et al., 2015). They have flash points (FPs) that are around room temperature, and they are extremely volatile and flammable (Qiao et al., 2020). They have the potential to start flames and explosions when combined with an oxidant and an ignite source. Second use batteries are even more dangerous. Second-use lithium-ion batteries refer to batteries that have been retired from their primary application. These batteries can be repurposed for other applications where their current state of health (SOH) and remaining capacity are sufficient. A research group in 2019 conducted a biological toxicity test on mice to find out the hazard batteries could pose to human beings (He et al., 2020). During the test, the mice exhibited signs of distress, such as stopping running, closing their eyes, shedding tears, and experiencing shortness of breath. The fact that some mice died during the 85% SOH experiment highlights the importance of safety considerations.

4 IMPROVEMENT DIRECTION

Li-O_2 and Li-S batteries have high specific energies, making them promising avenues for future research. Poor cycle performance and the stability and expense of electrocatalysts are some of the difficulties these technologies must overcome. Although lithium batteries dominate the performance-oriented market, they have a significant flaw in an era where sustainability is increasingly important. Therefore, it is crucial to focus not only on traditional metrics such as energy density and efficiency but also on the environmental impact. The industry is keen on advancing the electrochemical window and energy density of batteries. While these aspects are indeed appealing, it might be beneficial to consider enhancing safety and sustainability as well. The annual fatalities due to overheating of organic electrolytes are a significant concern. Many batteries still use organic electrolytes, which are extremely harmful to the environment (Flamme et al., 2017). The adoption of aqueous electrolytes could be a step towards rectifying this issue (Lebedeva and Boon-Brett, 2016).

5 CONCLUSION

In summary, lithium-ion batteries have dramatically improved the energy storage sector and provided a reliable and efficient platform for clean energy. Research on various cathode materials, such as NMC, LFP, and NCA, offers higher energy density and cycle life, with attendant safety and environmental concerns. This increased energy density demands greater thrust for new, innovative technologies, which include Lithium-air, solid-state, and lithium-sulfur batteries. However, these face significant hurdles, which include cycle performance and stability issues. Safety concern is still a prime issue, particularly that of thermal runaway; therefore, reasons are there for developing safer battery chemistries and designs further. Additionally, environmental hazards from the improper disposal of Li-ion batteries emphasize the need to have sustainable practices in manufacturing and recycling of batteries. The industry has to find a balance in pursuance of higher and higher energy densities in the quest for a balance with safety and sustainability imperatives. Going forward, Li-ion batteries should expect innovation only in developing materials and technologies to solve their drawbacks. A silicon anode, lithium-rich cathode, and high-voltage $LiCoO_2$ are being developed and are likely to bring significant increase in energy density. Shift towards using aqueous electrolytes may also provide a pathway towards a reduced environmental impact. The industry will have to prioritize research and development in these areas to ensure next-generation Li-ion batteries meet the energy demands of an increasing world population while at the same time aligning with our collective environmental goals. As we stand at the brink of a new energy storage era, the course for Li-ion batteries is driven toward convergence with technological innovation, environmental stewardship, and safety considerations. The way forward demands a concerted effort from researchers, industry leaders, and policymakers to chart a course that optimizes performance, safety, and sustainability. With such a focused drive toward these goals, the future of Li-ion batteries holds much promise in serving humanity's energy needs while contributing to a cleaner and more sustainable future.

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