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Viable Alternatives to Lithium-Based Batteries

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Abstract **Review Article**

Developing sustainable and environmentally friendly energy storage technologies for electric vehicles has become increasingly important with the growing demand for electric vehicles and increasing climate concerns. Lithium-ion batteries have been the primary energy storage technology used in electric vehicles due to their high energy density, long cycle life, and relatively low cost compared to other options. However, safety concerns related to the flammability of liquid electrolytes have motivated research on alternative energy storage technologies, mainly Sodium-ion and solid-state batteries. This paper reviews the status of sodium-ion and solid-state batteries as viable alternatives to lithium-ion batteries for electric vehicles. Sodium-ion batteries have shown promising results regarding energy density, safety, and cost but face challenges related to their lower specific energy and power density. Solid-state batteries have the potential to overcome many of the safety concerns associated with liquid electrolytes and exhibit high energy density but are currently limited by their high cost and low cycle life.

Keywords: electric vehicles, energy storage technologies, liquid electrolytes, sodium-ion.

INTRODUCTION

Lithium-ion batteries are the most common type of battery and is used in various electronic devices and a vast majority of Electric Vehicles (EVs). They are extremely common because of their high energy density relative to other electrical energy storage systems. On top of their high density, lithium batteries have also been shown to have a long life cycle and a low self-discharge rate. However, despite all the numerous benefits of lithium-ion batteries, there are also some downsides. The robustness of Lithium-ion batteries has been questioned, with constant protection required from being overcharged and discharged too far. Additionally, lithium batteries are shown to age poorly, with studies showing they can only last about 500-100 charge-discharge cycles before the battery's capacity starts to fall. Furthermore, the two most significant disadvantages of lithium batteries are its cost and the environmental impact of lithium mining as lithium-ion batteries are shown to be 40% more expensive to manufacture than Nickel-Cadmium batteries, and the mining process of lithium can cause immense environmental and habitat degradation. Despite these downfalls of Lithium-ion batteries, their upsides have primarily outweighed the costs. Almost every EV on the road today uses a lithium-ion battery, along with most electronic devices. However, EV growth in the automotive market can be a challenge for the lithium mining industry and, in turn, the automotive industry. As per a report by the International Energy Agency, a record 6.6 million EVs were sold worldwide in 2022, doubling the number from the year prior, and this has already been shown to put a strain on the Lithium market, although according to the Boston Consulting Group, there seems to be enough supply of lithium to meet demand up until 2025. Still, according to the report, "After [2025], chronic shortages are expected." By 2030, the Lithium supply is projected to be 4% less than demand, or about 100,000 metric tons short, and by 2035, the number is expected to rise to 24% short of demand. As the demand for EVs and lithium batteries is only going to rise, there will be a critical supply chain rupture. To ensure the safety of the EV market and to further the goal of making transportation as sustainable as possible, it is vital for there to be alternatives to Lithium-ion batteries. This research paper will compare lithium-ion batteries against their main alternatives, sodium-ion and nickel-cadmium batteries, in a conglomeration of reliability, energy density, cost of production, transportation, et cetera see if a replacement for the working-yet-flawed lithium-ion battery is here.

About EV Batteries

A battery is a device that stores chemical energy and converts it into electrical energy. Batteries comprise two main components, an anode, and a cathode, separated by an electrolyte. The chemical energy, stored in electrons, is in the anode, cathode, and electrolyte and is released when the battery is connected to an electrical circuit. When that happens, a chemical reaction occurs between the electrodes and the electrolyte, and the electrons from the anode flow to the cathode. However, they must go around the circuit, providing energy to the system. Batteries are split into two main groups, primary and secondary. Primary batteries, such as AA or AAA, cannot be recharged and are designed for single use only. They are primarily used in small electronic equipment, such as remotes, toys, and smoke detectors. On the other hand, secondary batteries can be recharged multiple times and are usually found in more extensive and complicated equipment, such as EVs, computers, and power tools, for which it would be both complicated and expensive to replace the battery every cycle. They have a shorter shelf life than primary batteries and are typically much more expensive, but they are more cost-effective in the long term as they can be reused multiple times rather than replaced every cycle. A “cycle,” in the context of a battery, refers to the process of charging and recharging a battery. For secondary batteries, a cycle is completed when a fully charged battery is discharged and recharged to its total capacity. Cycles are the standard unit of measuring a battery’s lifespan rather than time.

Lithium-ion Batteries

Currently, the most popular EV batteries are lithium-ion (Li-ion) batteries. They are named as such because the electrodes are made of lithium. As mentioned previously, Li-ion batteries are by far the most common batteries used in EVs, with over 60% of the EV battery market taken up by Li-ion batteries. Li-ion batteries are widely chosen for the batteries of new EV cars primarily because of their higher energy per mass, or their Energy density (measured in WH/L) has exceeded 450 by 2020, which is significantly higher than its main competitor in this market, the Nickel Hydride, whose energy density varies from 170 to 420 HW/L. Additionally, Li-ion batteries boast a competitive lifespan, with multiple experts from the energy industry guaranteeing a lifespan of 10-20 years while maintaining current charging speeds. Maintenance for a Li-ion battery is comparable to that of a combustion car, with the US Department of Energy’s Office of Energy Efficiency and Renewable Energy stating that the average cost of maintenance of an EV per mile is only $0.061 compared to $0.101 of the average combustion vehicle. The Lithium-ion battery’s downfalls are clearly visible when observing the cost of production and availability compared to future demand. Lithium, the main component of a Li-ion battery, is considered a “comparatively rare” element, as it is commonly found in rocks and natural saltwater but not in significant abundance. For an example of the high cost of production, the Bloomberg New Energy Finance report states that a lithium-ion battery is worth approximately $151/kWh, the highest it has ever been. High demand for EV batteries and the precious materials it has made from are among the many reasons batteries have been hiking up in price. Regarding future demand, EV sales have only been rising for the past few years, with record EV sales reported yearly. This puts immense strain on the mining industry, particularly lithium and cobalt mines.

Sodium-Ion Batteries

Lithium-ion (Li-ion) batteries are the dominant electric vehicle (EV) technology. However, sodium-ion (Na-ion) batteries have been gaining attention as a promising alternative due to their lower cost and higher abundance of sodium than lithium. Na-ion batteries have similar characteristics to Li-ion batteries, such as their ability to store and release energy, but with the added benefits of improved safety and sustainability.

Regarding energy density, Na-ion batteries have a slightly lower energy per mass than Li-ion batteries, with an energy density of around 100-200 Wh/kg compared to Li-ion's energy density of 250-350 Wh/kg. However, recent research has shown promising results in improving the energy density of Na-ion batteries by developing new electrode materials and structural designs. One of the main advantages of Na-ion batteries is their low cost, as sodium is much more abundant and, therefore, less expensive than lithium. Additionally, Na-ion batteries have a longer lifespan than Li-ion batteries, with an estimated lifespan of up to 15-20 years while maintaining current charging speeds. Maintenance costs for Na-ion batteries are also expected to be lower than for Li-ion batteries due to their more straightforward structure and lower risk of overheating or explosion. Despite these advantages, Na-ion batteries still face some challenges regarding their performance and commercialization. One of the significant challenges is the development of high-performance electrode materials that can achieve higher energy densities and longer cycle lives. Furthermore, the commercialization of Na-ion batteries is still in its early stages, and more research and development are needed to improve their performance and reduce their cost.

Critical Minerals in EV Batteries

Governments and businesses worldwide have expressed policies to accelerate EV adoption in transportation, indicating that the trend will likely continue. Projections suggest that by 2030, there could be a total of 200 million EVs sold, with approximately 6.6 million sold in 2021 alone. Compared to China and Europe, the U.S. EV market is relatively small, accounting for less than 10% of new global EV registrations in 2021. China and Europe accounted for 50% and 35% of new global EV registrations, respectively. The growth of electric vehicle (EV) sales has raised issues about securing the necessary mineral inputs used in EV batteries.

The congressional research service (August 2022) published a report on selected statistics for five EV battery minerals. The table below summarizes the findings:

	Lithium	Cobalt	Manganese	Nickel	Graphite
NIR (%)	>25	76	100	48	100
U.S. Production	withheld	700	0	18,000	0
Global Production	100,000	170,000	20,000,000	2,700,000	1,000,000
Exports	1,900	4,800	1,000	25,000	8,400
Imports	2,500	9,900	460,000	110,024	53,000
U.S. Reserves	750,000	69,000	0	340,000	not indicated

As per the report, the minerals are listed in a specific order, starting with lithium, used in all cathodes, followed by cobalt, manganese, and nickel. The mineral used in the anode, graphite, is listed after the cathode minerals. The section on "Secondary Mineral Supply" explores the option of EV battery recycling as a potential source for the five minerals. Each mineral is discussed in its subheading, with details on its mineralization and geological formation. Although this information may be highly technical, it can explain why certain minerals are found in geographically dispersed locations while others are concentrated in limited areas.

Concerns around EV Batteries

There is growing concern regarding the sustainability of lithium-ion EV batteries, which are not limited to just EV batteries. Lithium-ion batteries are utilized in billions of devices, such as cell phones, laptops, and other battery-powered devices. However, these concerns may be short-lived due to the rapid advancements in battery technology, and EV battery components may be significantly different shortly. Numerous companies invest significant resources in developing new battery technologies such as glass, lithium metal, lithium sulfur, sodium, graphene, and zinc air. One or more of these new technologies will likely emerge in the market within the next decade.

If lithium-ion remains the primary material used for EV batteries, the primary concerns include the following.

1. Ethical mining practices for cobalt.
2. The environmental impact of lithium extraction.
3. The availability of materials to meet the demand for EV batteries.
4. Carbon emissions from battery manufacturing; and
5. Toxic waste is produced from the disposal of used batteries.

Though batteries present a challenge for the electrification of the vehicle fleet, it is not insurmountable. The issues are well-known, and efforts are being made to address them. Electric vehicles can replace gasoline vehicles by exploring new sources of production, battery recycling, human rights issues in Africa, and changing battery technologies. Amnesty International called for creating an ethical and sustainable battery within five years that can be used for electric vehicles and in the electronics industry. Electric vehicle batteries come with an 8-year warranty of 100,000 miles, but new EV batteries last much longer, approaching up to 500,000 miles. In comparison, gasoline cars only last about 200,000 miles. Opting for an EV could be equivalent to getting two cars for the price of one. Additionally, approximately one-third of electric car drivers use rooftop solar panels as their source of electricity, saving fuel costs and reducing environmental impact. Gasoline is a pollutant that emits toxic air pollutants and can only be burned once, releasing 20 pounds of CO_2 per gallon, which stays in the atmosphere for thousands of years. Therefore, we should not halt the EV revolution due to concerns about electric vehicle batteries.

Future Material Demands

As per the report published in nature.com (https://www.nature.com/articles/s43246-020-00095-x), in a lithium nickel cobalt manganese oxide dominated EV battery scenario, demand is expected to increase by factors of 18–20 for lithium, 17–19 for cobalt, 28–31 for nickel, and 15–20 for most other materials from 2020 to 2050, requiring a drastic expansion of lithium, cobalt, and nickel supply chains and likely additional resource discovery. The uncertainties surrounding the topic are considerable, particularly regarding the electric vehicle fleet's development and battery capacity requirements per vehicle. However, the demand for cobalt and nickel would be substantially reduced if other battery chemistries, such as lithium iron phosphate or novel lithium-sulfur or lithium-air batteries, were used on a larger scale. Closed-loop recycling will play a minor but increasingly important role in reducing primary material demand until 2050. However, advancements in recycling are necessary to recover battery-grade materials from end-of-life batteries economically. The second use of electric vehicle batteries further delays the recycling potential.

Designing Better EV BHatteries

As researchers consider solid-state battery materials, they may also want to consider how they could impact large-scale manufacturing. traditional lithium-ion batteries continue to improve, but they have limitations that persist partly because of their structure. A lithium-ion battery comprises two positive and negative electrodes sandwiched around an organic (carbon-containing) liquid. As the battery is charged and discharged, electrically charged lithium particles (or ions) pass from one electrode to the other through the liquid electrolyte.

One problem with that design is that the liquid electrolyte can become volatile and catch fire at specific voltages and temperatures. Another problem is that lithium-ion batteries are not well-suited for use in vehicles. Large, heavy battery packs take up space and increase a vehicle's overall weight, reducing fuel efficiency. But it's proving difficult to make today's lithium-ion batteries smaller and lighter while maintaining their energy density —the amount of energy they store per gram of weight. As per an MIT report (https://news.mit.edu/2021/designing-better-batteries-electric-vehicles-0816), researchers are trying to solve this by changing critical features of the lithium-ion battery to make an all-solid, or "solid-state," version.

The conventional liquid electrolyte in batteries is replaced by a slim, stable solid electrolyte that can withstand various voltages and temperatures. Along with the solid electrolyte, a high-capacity positive electrode and a thinner-than-normal lithium metal negative electrode are utilized, replacing the typical porous carbon layer. These modifications make it feasible to significantly reduce the size of the battery while retaining its energy storage capacity, resulting in an increased energy density. MIT research demonstrates the importance of considering materials availability and supply chains when evaluating solid electrolytes for their scale-up potential.

MIT researchers suggest three broad questions to help identify potential constraints on future scale-up due to materials selection. The design should consider materials availability, supply chains, or price volatility in the context of production demands. It should also assess the impact on parts if fabricating batteries from these materials invokes difficult manufacturing steps. Lastly, it should review the impact on the cost of producing the batteries.

When evaluating the possibility of expanding the production of a battery design, it is essential to consider the complexity of the manufacturing process and how it could affect the cost. Developing a solid-state battery entails numerous procedures, and a mistake in any of these stages can lead to a higher cost per battery produced successfully.

One of the main challenges in designing an all-solid battery comes from "interfaces" or points of interaction between components. During manufacturing or operation, materials at those interfaces can become unstable. Therefore, much research is focused on developing ways to stabilize interfaces in various battery designs. Although many proposed solutions increase performance, the battery cost in dollars per kWh decreases.

However, implementing these solutions usually entails additional materials and time, resulting in a higher cost per kWh during mass production. Enhancing the gravimetric energy density of electric vehicles is critical to improving their commercialization.

This is measured in Watt-hours per kilogram and can be achieved using safer, more easily recyclable, abundant materials. Lithium-metal anodes are considered the ultimate objective for enhancing energy density in EV batteries compared to existing choices, such as graphite, which has a 240 Wh/kg rating.

This development is essential to achieving more competitive energy density, to reach 500 Wh/kg. In just ten years, significant progress around EV batteries has been made in the past decade. We must consider alternatives as the demand increases to ensure the desired supply. The next decade will be interesting for the EVs.

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