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Sustainability and Safety Challenges of Battery Electric Vehicles: Environmental Impacts and Safety

Mingzi Chen

UNSW, Sydney, Australia
mingzic926@gmial.com

Abstract: The rapid development of battery electric vehicles (BEVs) has reshaped the global automotive industry, offering significant contributions to emission reduction and the transition toward renewable energy. However, the widespread adoption of BEVs presents notable challenges, including environmental impacts from battery production, resource scarcity, recycling difficulties, and safety concerns. This paper examines these key issues, focusing on the excessive energy consumption and greenhouse gas emissions caused by lithium battery manufacturing, the environmental risks associated with improper recycling methods, and the safety hazards posed by battery degradation and thermal runaway events. Furthermore, the study explores emerging solutions such as green hydrometallurgy, robotic disassembly, and the potential of sodium-ion batteries as a safer and more sustainable alternative. Looking ahead, technological innovation, intelligent battery management systems, and strong policy support are essential for overcoming these challenges and shaping the future of sustainable transportation.

Keywords: Battery electric vehicles (BEVs), lithium-ion batteries, carbon emissions, battery recycling, thermal runaway

1. Introduction

In the past period, new energy electric vehicles have greatly affected the world dominated by oil vehicles. Among them, the lithium battery industry chain has become a hot topic, and car companies and chemical plants are also competing to optimize lithium battery technology. The application of lithium battery technology not only expands the automobile market, but also enriches customer choices, and promotes economic development; most importantly, it can reduce greenhouse gas emissions and promote renewable energy. Since 2010, electric vehicle sales have repeatedly broken records, and global electric vehicle manufacturers have guaranteed that more than $140 billion will be spent on transportation electrification.

While BEVs hold immense potential for decarbonization, their widespread adoption faces dual barriers: the environmental burdens embedded in lithium-ion battery supply chains and unresolved safety risks associated with battery operation. Given the increasingly prominent role that battery electric vehicles (BEVs) are expected to assume in future transportation systems, it is essential to acknowledge that their operation and production also exert substantial environmental impacts. The carbon emissions associated with manufacturing an electric vehicle is estimated to be approximately 1.2 times those generated in the production of a conventional gasoline-powered vehicle. This disparity is largely attributable to the energy-intensive processes involved in the production of

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lithium-ion batteries, particularly the extraction and refinement of raw materials. By the year 2030, the global fleet of electric vehicles is expected to exceed 125 million units, with lithium-ion batteries serving as the fundamental component powering these vehicles. At present, the substitution of fossil fuels with renewable energy sources delivered via electricity as the primary energy carrier for transportation has become one of the principal measures adopted by the automotive industry to reduce carbon dioxide emissions.

However, as the base of electric vehicles grows, power batteries are also facing many challenges, such as environmental, safety, materials, and recycling. This research aims to investigate the challenges and opportunities faced by Battery Electric Vehicles and explore how the industry can shape the future of Battery Electric Vehicles. It analyzes how excessive demand for energy leads to large amounts of greenhouse gas emissions and how to solve them and explores what are the main challenges faced by renewable energy integration and power battery recycling during circulation and how to deal with them. It would also analyze the impact of power battery safety issues on Battery Electric Vehicles and how to gain public trust.

2. Environmental impact of lithium-ion battery production

2.1. Carbon footprint of lithium-ion batteries

Lithium-ion batteries are widely recognized for their numerous advantages, including high capacity, elevated specific energy, and a low self-discharge rate. The confluence of these features has led to the exponential growth in demand for lithium-ion battery technologies [1]. Continued advancements in battery design and efficiency are anticipated to play a pivotal role in reducing global greenhouse gas emissions and improving overall air quality. However, it is critical to emphasize that much of the environmental burden arises from upstream activities in the electric vehicle supply chain—specifically, the mining and processing of raw materials. For instance, the production of lithium-ion batteries necessary for electric vehicle assembly results in higher carbon dioxide emissions compared to the manufacturing processes for traditional gasoline vehicles. Approximately 40% of the total greenhouse gas emissions are associated with lithium-ion battery production originate from mineral extraction and processing. [2] Moreover, large-scale commercial mining activities targeting lithium, cassiterite, lead, zinc, and tantalum are linked to significant environmental degradation, including the deterioration of vegetation, landscape alteration, loss of arable land, and other adverse ecological consequences. [3]

2.2. Resource extraction and ecological risks

One primary approach to obtaining lithium involves saline water harvesting techniques. [4] The primary extraction technique involves strategic injection of water volumes into underground salar formations to recover lithium-rich brines through natural capillary action.Sequential sun-driven evaporation and controlled crystallization techniques facilitate optimized mineral extraction. Significantly, the Lithium Belt - encompassing parched territories across Chile, Bolivia, and Argentina - harbors nearly 50% of global commercially extractable lithium deposits. This unique geological formation experiences heightened ecological strain as brine extraction modifies underground hydrology, intensifying hydrological deficits in sensitive dryland biomes. The escalating clash between industrial mining activities and watershed protection initiatives underscores critical resource management dilemmas in metal-rich xeric environments.

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2.3. Impact of battery degradation

In addition to environmental risks, there are technical constraints in the field of electric vehicle application caused by the attenuation of energy storage efficiency. Research data show that when the battery capacity retention rate drops to the original 30% (70% lower than the initial specification), its performance degradation will lead to significant energy consumption changes: compared with the ideal condition, the power consumption per kilometer increases by 11.5%-16.2%, corresponding to a synchronous rise in carbon dioxide emissions [5]. This set of data confirms that only through three major technological breakthrough paths - improving the thermal control architecture, strengthening the mechanical pressure performance, and improving the time-dimension service capability - can the innovation of electrochemical energy storage systems be fundamentally promoted. After the realization of these technological upgrades, the power battery truly has the environment-friendly characteristics of the whole life cycle, and effectively avoids the asymmetric pollution increase that may be generated during the decline period of product performance.

2.4. Innovations in sustainable battery production

Mitigating global ecological challenges remains imperative as scientific communities explore innovative methodologies for practical implementation pathways. In industrial development, significant focus has shifted toward optimizing targeted lithium extraction methods, notably pressurized sorption-based Direct Lithium Extraction (DLE) mechanisms. These advancements improve sustainable resource management through specialized isolation of lithium compounds and strategic minerals from briny reservoirs, displacing traditional solar evaporation basins with closed-loop recovery protocols demonstrating reduced environmental footprint [6]. Complementary progress in intelligent thermal management systems - particularly activating battery cooling mechanisms for stationary vehicles exposed to ambient temperatures surpassing 28°C - yields measurable improvements in energy cell durability, achieving 18-22% reductions in lifecycle carbon emissions for electrochemical storage units [5].

System safety optimization concurrently emerges as an essential factor influencing ecological sustainability in energy storage applications. The synergistic relationship between environmental conservation objectives and operational risk management critically determines public acceptance and commercial feasibility of electrified transport systems, collectively shaping progressive development of decarbonized transit networks. Through maintaining technical robustness in energy storage operations, institutions not only guarantee system dependability but also reinforce stakeholder trust in renewable energy repositories, establishing fundamental prerequisites for mainstream implementation of eco-conscious mobility frameworks.

3. Challenges and solutions in lithium-ion battery recycling

3.1. Current recycling practices and their limitations

With the worldwide adoption of electric cars accelerating, expired LIB systems present an emerging strategic challenge. Industry reports indicate waste volumes from spent lithium-ion power cells could surpass 11 million tonnes globally by 2030 [7]. Inadequate recycling infrastructure creates triple sustainability risks: groundwater pollution from toxic leachates, permanent loss of rare metal reserves (20-35% Co/Ni/Li recovery loss), and preventable landfill occupation exceeding 2,500 football fields annually. Current analysis reveals 42-58% of retired automotive LIB units face improper storage or unregulated disposal - practices enabling electrolyte decomposition processes that degrade agricultural productivity through soil acidification while discarding recoverable energy equivalents to 15M barrels of crude oil annually.

Currently, power battery recycling is undertaken through three principal methods: physical recycling, pyrometallurgy, and hydrometallurgy. Physical recycling is characterized by low energy consumption and involves mechanical disassembly, crushing, and screening to recover metals such as copper and aluminum. However, the significant diversity in battery pack structures and designs complicates disassembly processes, leading to lower efficiency and economic returns [7]. Pyrometallurgy, in contrast, employs high-temperature smelting techniques to recover critical metals such as cobalt and nickel. Despite its effectiveness in material recovery, pyrometallurgy is highly energy-intensive and generates substantial quantities of toxic emissions, contributing to environmental degradation [8]. Hydrometallurgy, the most widely adopted recycling method, involves using chemical reagents to dissolve battery materials, achieving recovery rates as high as 90%. Nonetheless, hydrometallurgical processes are associated with high operational costs and pose considerable environmental hazards if waste liquids are not adequately treated. Furthermore, different battery components' varying material value and extraction complexities necessitate careful trade-offs in recovery strategies. The mass disassembly, refurbishment, and remanufacturing of batteries present logistical and environmental challenges that require coordinated industrial efforts. Harper et al. further report a concerning increase in the number of fires at metal recycling facilities, highlighting the safety risks associated with improper handling of battery waste. [9]

3.2. Emerging recycling technologies and practices

Nonetheless, governments, enterprises, and academic researchers are collaboratively pursuing innovative solutions. The increasing sophistication of artificial intelligence technologies has enabled the deployment of automated systems capable of undertaking battery disassembly with high precision and minimal risk. According to Harper et al. , robotic systems can safely cut and disassemble contaminated waste materials in hazardous environments, including those with radiation risks. [9] In parallel, the promotion of green hydrometallurgy — utilizing bio-organic acid solvents to reduce the environmental impact of acidic waste liquids — has become a focal point in battery recycling research (Harper et al., 2019). [9] Moreover, policy and market-based interventions are playing an instrumental role in facilitating more efficient recycling frameworks. Initiatives such as retaining battery ownership by vehicle manufacturers (with consumers paying usage fees rather than purchasing the batteries outright) have demonstrated efficacy in improving recycling rates. Additionally, financial incentives for manufacturers who utilize recycled materials in battery production have proven effective in encouraging circular economy practices [8].

Promoting sustainable transit solutions necessitates equal focus on ecosystem preservation and secure energy storage mechanisms to uphold civic confidence. Documented cases of thermal runaway incidents in power cells reveal that equipment failures threaten both physical wellbeing and societal acceptance of emission-free mobility. Consequently, advancing protective engineering measures must develop in tandem with renewable production methods and circular material economy strategies, ensuring ecological progress aligns with fail-safe technological standards. This balanced approach addresses twin imperatives - environmental conservation through reduced resource consumption and accident prevention through robust system designs.

4. Safety concerns of battery electric vehicles

While ongoing improvements continue, persistent safety issues stand as a primary obstacle to mainstream adoption of electric vehicles. Statistically, lithium-ion battery incidents involving thermal runaway events occur at extremely low rates (estimated between 0.1-1 per million units), yet extensive media reporting of such cases has created disproportionate public apprehensions [10].Documented vehicle fire incidents reveal critical vulnerabilities, including the 2019 thermal

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runaway incident affecting a Tesla sedan in a Shanghai residential complex [11], along with 15 documented Hyundai Kona battery failures across multiple markets from 2020-2021, stemming from production flaws in battery modules [12]. These occurrences highlight the imperative for advancing fail-safe technologies and quality control protocols in electrochemical energy storage systems.

4.1. Battery failure

The safety risks of the lithium battery system mainly come from a variety of failure causes: mechanical damage to the diaphragm, internal short circuit of the battery cell, structural deformation caused by collision, heat dissipation failure during charging and local thermal shock, etc. These abnormal states can jointly trigger the thermal runaway process [13]. Thermal runaway is essentially a chain effect caused by irreversible exothermic reaction when the temperature reaches the critical threshold of 80 degrees Celsius, with significant safety hazards [14]. In terms of charging safety regulations, the current mainstream charging mode relies on cables and charging piles to conduct energy transmission [15], but there is a risk of spontaneous combustion or deflagration caused by the coupling of abnormal temperature rise of wires and potential short circuit of batteries.

4.2. Solutions to battery failure

For the improvement of safety performance, industry experts have proposed targeted technical research directions. As the core solution support, the intelligent battery management system (BMS) monitors the pressure difference evolution, temperature field distribution and current dynamic balance in the charge and discharge process through a group of interconnected sensors. Its parameter tracking mechanism in continuous operation can not only standardize the charge and discharge parameter threshold, but also isolate potential thermal runaway incentives in time [15,16]. At the level of industrial chain collaboration, the strategic alliance of enterprises is promoting the engineering application of OTA technology, prompting manufacturers to realize the iterative optimization of power supply system through the wireless transmission performance correction scheme [17]. These innovations form a technological loop with a central diagnostic platform based on predictive models that can accurately identify signs of aging of the battery microstructure using electrochemical signature analysis.

In the field of alternative technologies, sodium-based energy storage systems show unique resource advantages. The widespread occurrence of sodium elements in seawater layer and crust makes its exploitation process have significant ecological advantages over lithium resources, and greatly reduces the risk of environmental disturbance [18]. Especially in the dimension of temperature resistance, sodium ion components show excellent temperature stability under different load environments, which makes the runaway threshold of heat release at the system level significantly higher than that of traditional schemes [19]. However, it should be pointed out that the power consumption disadvantage caused by the existing energy storage density difference still needs to achieve breakthrough progress through material science innovation and process improvement, especially in terms of module integration efficiency and full life cycle cost control, the research and development layout must be accelerated to match the commercialization maturity of mainstream lithium battery systems.

5. Conclusion

In recent years, pure electric vehicles (BEVs) have profoundly revolutionized the automotive industry landscape, helping to reduce carbon emissions and promote clean energy. Its explosive development has derived a double problem: the interactive superposition of the environmental impact and safety risks generated by the battery's full cycle. Only by breaking through the environmental

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bottleneck of lithium resource development and recycling system, and overcoming the innovation problem of thermal runaway protection and battery core technology, can we ensure the sustainable development of the industry. Of particular concern is that sodium-ion battery technology, by taking into account raw material sustainability and structural stability, is forming an innovative path to synergistically solve the two dilemmas.

In the field of battery recycling, hydrometallurgy is known for efficient extraction, but it has long faced the double test of economic pressure and process waste liquid control. Although new solutions such as green purification technology and intelligent dismantling equipment have shown potential, they are still in the process of technology transformation. The safety dimension directly affects the market recognition, and frequent thermal runaway accidents highlight the necessity of upgrading intelligent monitoring systems - the construction of cloud early warning platform and distributed thermal management network has become a requirement of the industry. The sodium-electric technology, which has the characteristics of resource friendliness, environmental adaptability and thermal stability, although it still needs performance optimization, undoubtedly provides a new idea for the next generation of energy storage solutions.

To achieve the development goals of two-wheel drive, it is necessary to establish a systematic framework for environmental governance and safety. The policy level should simultaneously promote the circular economy incentive mechanism and the research and development investment of intelligent battery management technology. It is worth noting that artificial intelligence is forming a breakthrough in technology integration: AI-driven precision disassembly and dynamic failure prediction technology, showing the possibility of improving resource utilization efficiency and accident prevention ability at the same time. This multi-dimensional technical synergy will determine whether electric vehicles can truly break through the development bottleneck and become a green travel solution with social universality.

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