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Research Paper

Sustainable Electric Vehicle Batteries: Recycling, Second-Life Applications and Circular Economy

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Abstract
The exponential expansion of the electric vehicle (EV) market has significantly increased the demand for lithium-ion batteries, thereby introducing a variety of environmental, economic, and technological challenges related to battery lifecycle management. Consequently, the development of sustainable battery systems has emerged as a critical priority to ensure the long-term availability of resources and mitigate ecological impacts. This review critically explores recent advancements in sustainable management strategies for EV batteries, with a particular focus on recycling technologies, second-life applications, and circular economy principles. It examines the viability of repurposing retired EV batteries for applications such as stationary energy storage, integration with renewable energy systems, and support for smart grid technologies. Additionally, the review addresses global challenges anticipated by 2026—such as geopolitical tensions, disruptions in supply chains, and rising costs of critical battery materials—and evaluates their potential repercussions on efforts to achieve battery sustainability. Furthermore, the study underscores the importance of these technological advancements in the context of engineering education, particularly within automotive engineering programs at the Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen University. Incorporating circular battery management technologies into academic curricula is proposed as a means to prepare future engineers with the specialized knowledge and skills necessary to drive progress in sustainable energy systems and adapt to the evolving landscape of the EV industry.

Keywords: *Electric vehicle batteries; Battery recycling; Second-life batteries; Circular economy; Sustainable energy storage.*

I. Introduction

The global shift toward low-carbon transportation has catalyzed an unprecedented adoption of electric vehicles (EVs) across the world. This transformation is driven by an urgent imperative to address greenhouse gas emissions, enhance air quality, and reduce dependence on fossil fuel-based energy sources. In this context, governments and industrial stakeholders have allocated considerable investments toward EV-related technologies, with lithium-ion batteries emerging as the predominant energy storage solution due to their high energy density, prolonged cycle life, and matured manufacturing infrastructure. However, the rapid proliferation of EVs has highlighted significant challenges concerning the sustainability of battery production and end-of-life management. The core materials utilized in these batteries—such as lithium, cobalt, nickel, and graphite—are extracted through processes that are often environmentally detrimental. Furthermore, the expected exponential increase in EV deployments over the coming decades is projected to generate substantial volumes of decommissioned batteries, presenting critical issues for waste management systems that must accommodate these retired units. Conventional linear economic models, which prioritize resource extraction, utilization, and subsequent disposal, fall short in addressing the complexities of EV battery lifecycles. As a response to these limitations, circular economy principles have emerged as a practical framework for enhancing resource efficiency while mitigating environmental impacts. Circular strategies focus on extending the operational lifespan of batteries through reuse, innovative recycling methods, and second-life applications. Among these approaches, second-life utilization of EV batteries has gained considerable traction in recent studies and industrial practices. Importantly, EV batteries that have been decommissioned from vehicles typically retain approximately 70–80% of their original capacity. While this diminished performance precludes their continued use in automotive roles, it makes them highly suitable for stationary energy storage applications. The repurposing of these batteries not only prolongs their functional lives but concurrently reduces the demand for manufacturing new ones—a benefit with both economic and environmental dimensions. In parallel, breakthroughs in recycling technologies offer promising avenues for reclaiming critical materials from end-of-life batteries. State-of-the-art recycling processes now allow for the efficient recovery of essential elements such as lithium, cobalt, and nickel, enabling their reintegration into battery production cycles. These advancements serve dual purposes: reducing environmental harm related to battery disposal while safeguarding resource availability amidst growing demand within global supply chains. Beyond technical considerations, the sustainability of EV batteries is increasingly shaped by broader geopolitical and economic factors. Recent occurrences such as international conflicts, trade wars, and disruptions in mineral supply chains have significantly influenced the cost-effectiveness and accessibility of key battery materials. Concurrently, rising energy prices coupled with accelerating trends in electrification underscore the need for resilient strategies aimed at managing battery lifecycle sustainability. Addressing these intersecting challenges necessitates the establishment of robust circular ecosystems for EV batteries. To secure the long-term viability of the industry, integrating second-life applications, advanced recycling methods, and circular supply chain models into current systems is imperative. Equally important is the role of education in equipping future engineers to tackle these multifaceted challenges. Academic institutions must adapt curricula to embed concepts related to circular economic frameworks, sustainable battery systems, and advanced energy storage technologies. For example, initiatives undertaken at Thai Nguyen University of Technology—Thai Nguyen University—through its Faculty of Vehicle and Energy Engineering aim to prepare engineering graduates to innovate environmentally sustainable transportation solutions by incorporating these critical themes into their academic programs. Such efforts are pivotal in fostering a workforce capable of addressing contemporary sustainability demands while advancing the technological frontier of low-carbon mobility systems.

II. Contents

2.1 Lifecycle of Electric Vehicle Batteries

The lifecycle of electric vehicle (EV) batteries is a complex process with four distinct stages: raw material extraction, battery manufacturing, vehicle operation, and end-of-life management. Each phase presents unique environmental, economic, and technological challenges, which must be addressed to ensure the sustainability of these batteries throughout their lifespan. The initial stage involves the extraction of critical raw materials essential for lithium-ion battery production. Key components such as lithium, cobalt, nickel, manganese, and graphite are mined to meet global demand. However, the extraction and supply of these materials come with challenges. Many of these resources are geographically concentrated in just a few countries, creating potential risks surrounding supply chain stability and geopolitical dependencies. For instance, the Democratic Republic of Congo dominates global cobalt production, while significant lithium reserves are situated in South America—primarily in the "Lithium Triangle" involving Chile, Argentina, and Bolivia—and other regions such as Australia. These geographical concentrations underline the need for sustainable mining practices and the diversification of sourcing strategies. Once raw materials are procured, they are used in the manufacturing phase to create EV batteries. These highly technical processes result in batteries that power electric vehicles during their operational lifetimes. In this second stage of the lifecycle, the batteries experience gradual degradation caused by complex electrochemical reactions, exposure to varying temperature conditions, and the repeated charging and discharging cycles that sustain their performance. Over time, typically after several years of use, battery capacity diminishes to approximately 70–80% of its original state. Once this threshold is reached, the battery may no longer meet the rigorous performance standards required for electric vehicle operation. Despite this reduction in capacity, EV batteries retain a considerable amount of energy storage ability even after their primary automotive use. Instead of being immediately discarded, these batteries can be given a second life by being repurposed for alternative applications, such as powering stationary energy storage systems. These systems play a crucial role in stabilizing renewable energy grids or supporting local power needs during peak demand. By transitioning into secondary applications, the overall utility of an EV battery can be effectively extended for an additional 5 to 10 years, further enhancing its lifecycle value. Eventually, after a battery has reached a stage where it is no longer viable for either vehicular use or secondary applications, it transitions into the final stage of end-of-life management: recycling. Modern recycling processes employ advanced technologies designed to recover high-value materials like lithium, cobalt, nickel, and manganese. These reclaimed materials can then be reintegrated into the production of new batteries, contributing to the circular economy and reducing dependency on raw material extraction. This recycling phase not only minimizes environmental footprints but also helps mitigate resource scarcity concerns. Ultimately, understanding and addressing the complexities within each stage of an EV battery's lifecycle is vital for advancing a sustainable future for electric vehicles. By improving efficiency across these steps—through responsible sourcing practices, robust manufacturing standards, innovative reuse models, and cutting-edge recycling technologies—the environmental impact of battery production and disposal can be significantly reduced while supporting the broader shift towards green energy solutions.

2.2 Second-Life Applications of EV Batteries

The concept of second-life applications for electric vehicle (EV) batteries has gained significant traction as an impactful strategy to enhance both sustainability and the economic efficiency of battery lifecycle management. Lithium-ion batteries used in EVs typically reach the end of their automotive utility when their energy capacity decreases to about 70–80% of the original. At this stage, these batteries may no longer fulfill the rigorous demands of EV power and energy requirements but still possess substantial energy storage capabilities. This remaining capacity makes them ideal candidates for reuse in less demanding stationary energy storage applications. By repurposing these batteries, their lifespan can be significantly extended, waste generation minimized, and the overall efficiency of resource utilization within the battery ecosystem vastly improved. One of the most explored second-life battery applications is residential energy storage. Retired EV batteries can be repurposed into systems designed to store electricity generated from sources like rooftop solar panels. These systems allow homeowners to save surplus solar energy produced during the day for use at night or during peak electricity demand periods. This not only reduces dependence on conventional electricity grids but also leads to lower electricity costs and better utilization of renewable energy sources. Such systems can also help improve energy resilience by providing backup power during outages, ensuring essential household systems continue to operate seamlessly. Another prominent use case for second-life EV batteries lies in grid-scale energy storage. With renewable energy sources like solar and wind becoming integral to modern power grids, addressing their intermittent and unpredictable nature remains a priority. Energy storage systems help bridge the gap between energy supply and demand, storing excess production during high-generation periods and releasing it when demand outpaces supply. Second-life batteries offer an affordable solution for large-scale stationary energy storage, as their reduced performance is offset by lower costs compared to new batteries. In these applications, retired batteries can assist with critical grid functions such as frequency regulation, voltage stabilization, and peak load management, collectively boosting grid reliability and operational efficiency. Microgrid systems also present exciting opportunities for second-life EV batteries. Microgrids are localized energy networks capable of operating independently from the larger grid, making them particularly appealing for remote or rural areas with limited or unreliable grid access. In such setups, second-life batteries can store excess energy generated by renewable sources like solar or wind and provide steady power to local communities. This not only enhances energy access in underserved regions but also curbs reliance on environmentally harmful diesel generators, contributing to both economic and environmental benefits. In addition to residential and grid-scale applications, second-life batteries are increasingly used in backup power systems for commercial and industrial facilities. Data centers, hospitals, telecommunications hubs, and office buildings all require uninterrupted power to support critical operations during grid outages or fluctuations. In these scenarios, second-life batteries serve as reliable backup systems capable of providing the necessary power without the high cost associated with new batteries. While these applications demand high reliability and durability rather than maximum energy density, properly managed second-life batteries are well-equipped to meet such requirements. Despite their promising potential, the widespread adoption of second-life battery applications faces several technical and economic challenges. A significant hurdle lies in the variability of battery performance among retired units. Variations in operating conditions during their first life can lead to disparities in residual capacity, internal resistance, and overall degradation. This poses challenges for sorting, testing, and repurposing processes, as each battery may require individual assessment. Additionally, safety concerns related to degradation, thermal instability, and potential internal damage demand careful mitigation strategies to ensure safe operation of second-life systems. Consequently, developing standardized testing protocols and diagnostic methods for evaluating battery health has become a critical area of research. Economic factors also play a pivotal role—cost-efficient methods for collecting, transporting, testing, and repurposing used batteries are essential to making these applications commercially viable and sustainable. By addressing these challenges through innovation and standardization, the adoption of second-life EV batteries could pave the way for more sustainable energy ecosystems while offering substantial economic benefits across various sectors.

2.3 Recycling Technologies for EV Batteries

Battery recycling is an essential pillar in advancing a circular economy for electric vehicle (EV) batteries. It facilitates the recovery of valuable materials while mitigating the environmental risks associated with battery disposal. Lithium-ion batteries, common in EVs, contain critical materials like lithium, cobalt, nickel, manganese, and copper. These resources are economically significant but extracting them from natural reserves poses substantial environmental challenges. Recycling helps reduce dependency on raw material mining and minimizes the ecological damage caused by improper waste handling. There are currently three primary approaches to recycling lithium-ion batteries: pyrometallurgical recycling, hydrometallurgical recycling, and direct recycling. Each method varies in terms of efficiency, environmental impact, and cost-effectiveness. Pyrometallurgical recycling employs high-temperature smelting to convert battery components into metallic alloys and slag while recovering metals like cobalt, nickel, and copper. This method is widely used because it can process mixed battery waste without extensive sorting. However, it has its limitations. The process is energy-intensive due to the high temperatures required and often fails to fully recover lighter materials, such as lithium and aluminum. Additionally, it generates greenhouse gas emissions and toxic by-products that necessitate further treatment, adding to its environmental impact. Hydrometallurgical recycling has gained attention as a more efficient and environmentally friendly alternative. It uses chemical leaching to dissolve battery components, followed by the extraction of valuable metals through precipitation, solvent extraction, or electrochemical processes. When optimized, this method achieves recovery rates of over 90% for materials such as lithium, cobalt, and nickel. Its lower operating temperatures reduce energy consumption and result in a smaller carbon footprint compared to pyrometallurgy. However, it also demands stringent management of chemical reagents and wastewater to prevent environmental contamination. Direct recycling represents a cutting-edge approach that focuses on preserving the cathode materials' original crystalline structure instead of breaking them down into individual elements. This method enables these materials to be directly reused in new batteries, potentially reducing energy demands and processing costs compared to traditional recycling techniques. However, as a relatively new innovation still in the research and development phase, direct recycling faces challenges such as ensuring effective purification, scaling up for industrial use, and accommodating diverse battery chemistries. Enhancing recycling technologies is critical to sustaining the rapid expansion of the electric vehicle sector. With the growing number of EV batteries reaching the end of their life span in the coming years, expanding efficient and sustainable recycling systems will be imperative. This will not only help manage increasing battery waste but also ensure the recovery of critical materials for future energy storage solutions.

2.4 Global Challenges in 2026 and Their Impact on Sustainable EV Batteries

The global energy and transportation sector in 2026 is marked by considerable economic unpredictability and heightened geopolitical tensions. The growing adoption of electric vehicles (EVs) has spurred intense competition for critical battery materials such as lithium, nickel, and cobalt—key components in modern battery technologies. However, the production and supply of these materials are heavily concentrated in specific regions, leading to vulnerabilities in global supply chains. Geopolitical strife, trade disputes, and resource nationalism have exacerbated the volatility of mineral markets worldwide. For example, lithium production is largely confined to South America, Australia, and China, while the Democratic Republic of Congo remains the dominant player in cobalt mining. Political instability, export controls, or regulatory shifts in these regions could disrupt supply and create significant challenges for battery manufacturers. Beyond these geopolitical dynamics, the rapid expansion of the EV industry has substantially driven up demand for battery materials. With millions of electric vehicles entering global markets annually, the need for lithium-ion batteries has skyrocketed. Consequently, raw material prices have become increasingly volatile, driving higher production costs for batteries and influencing the broader affordability of EVs. Simultaneously, escalating fossil fuel costs and intensifying concerns over climate change are pushing a global shift toward electrified transportation systems. Governments across the world are adopting policies to curb carbon emissions and promote renewable energy initiatives. These include financial incentives for EV purchases, increased investments in charging infrastructure, and stricter emission standards for traditional internal combustion engine vehicles. In this evolving scenario, sustainable battery management strategies are becoming vital. Recycling technologies offer an opportunity to recover valuable metals from end-of-life batteries, reducing reliance on newly mined resources. Additionally, second-life applications allow batteries to serve alternative purposes before they enter the recycling phase. By integrating these approaches into a circular battery economy, the resource efficiency of EV battery systems can be significantly enhanced while mitigating environmental impacts and addressing supply chain vulnerabilities.

2.5 Implications for Automotive Engineering Education at Thai Nguyen University of Technology

The rapid advancement of electric vehicle (EV) technology and sustainable battery systems is reshaping engineering education. Automotive engineers must now gain interdisciplinary expertise, covering mechanical and electrical engineering, materials science, and environmental sustainability. At Thai Nguyen University's Faculty of Vehicle and Energy Engineering, incorporating cutting-edge battery technologies into the curriculum is critical to preparing students for the demands of the evolving transportation sector. Key course topics should include battery chemistry, degradation, management systems, and energy storage. Understanding battery lifecycle management is essential for sustainable transportation. Students should explore concepts like reuse, second-life applications, recycling, and the circular economy. These insights can drive environmentally conscious EV advancements. Hands-on labs and research projects can enhance learning by offering practical experience with battery testing, thermal systems, and management design. Partnerships with industry and research institutions can provide internships, collaborative projects, and real-world problem-solving opportunities. By adopting these approaches, universities can cultivate engineers ready to lead in sustainable transportation and support the global shift to electric mobility. Future research should focus on making EV batteries more efficient, safe, and economically viable. Innovations in recycling technologies, such as automated disassembly and advanced material separation, are crucial for maximizing material recovery while minimizing environmental impact. Developing standard methods to assess the health of used batteries is also crucial for determining their reuse or recycling potential. AI-driven diagnostic tools and advanced digital management systems are expected to play a central role in optimizing battery lifecycles by predicting wear, improving charging protocols, and extending lifespans. Next-generation battery designs emphasizing sustainability are another research priority. Modular construction, standardized components, and easily dismantled materials could simplify recycling and promote a circular battery economy.

III. Conclusion

The growing adoption of electric vehicles has introduced challenges in battery sustainability and resource management. Solutions like second-life battery uses, advanced recycling, and circular economy practices offer ways to address these issues by prolonging battery life and recovering key materials, enhancing EV industry sustainability. Meanwhile, global geopolitical and economic dynamics underscore the need for robust resource management. Incorporating sustainable battery technologies into automotive engineering education is vital to equipping future engineers with the skills to create environmentally responsible transportation..

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