The Double-Edged Sword of Sustainability: Lithium-ion Batteries, Environmental Impacts and Opportunities for Improvement

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Abstract. This comprehensive study investigates the multifaceted impacts of LIBs(LIBs) and sustainable framework for repurposing used LIBs. The rapid proliferation of LIBs in electric vehicles and consumer electronics has raised concerns about their environmental footprint, disposal implications, and resource depletion. To address these issues, this paper aims to evaluate various technologies that facilitate an environmentally friendly method for prolonging battery life cycles. A systematic process for collecting, assessing, and refurbishing batteries will be developed to identify potential secondary uses such as home energy storage systems, backup power solutions, and small-scale renewable energy projects. The study will investigate the environmental consequences of LIB manufacturing and disposal, including electronic waste generation, resource depletion, and contamination risks, and explore the role of repurposed LIBs in reducing e-waste and conserving resources, this research seeks to contribute significantly To advance environmentally friendly battery management practices and foster a more circular economy, the research aims to provide valuable insights. These findings will have significant implications for various sectors, including industries, policymakers, and consumers. By promoting sustainable development, the research seeks to eliminate the impact of LIBs(LIBs) on the environment.

Keywords: LIBs, Sustainable Frameworks, Reuse

1. Introduction

Batteries are indispensable to our daily lives, powering a wide range of devices and systems, from compact electronics like mobile phones and handheld computers to heavy industry infrastructures like electric vehicles and renewable energy storage systems.

The concept of LIBs was introduced in the 1970s when M. S. Whittingham conducted research on lithium-based electrochemical storage. Sony commercialized LIB technology in the 1990s, revolutionizing portable electronics and subsequently impacting the electric vehicle sector. Ongoing advancements in LIB technology have led to extensive applications, with ongoing research focused on enhancing energy density, charge cycles, and sustainability.

The growing interest in EV was been significant over the last 10 years and is expected to expand rapidly in the near future. This demands to create a substantial market for repurposed batteries. In 2020, the supply of LIBs reached 1 GWh, while the demand for more general purpose energy storage surpassed 7 GWh (Juner Zhu, 2021). Projections indicate that by 2025, the annual supply of used batteries could increase to 15 GWh under both conventional and innovative scenarios. Furthermore, by the end of another decade EV's may contribute over 200 GWh annually in the innovative scenario, surpassing the demand for LIBs in general purpose energy storage (Md.Tanjil Sarker, 2024). The early predictions suggest that the western countries, and China will emerge as the leaders in terms of exporting of repurposed batteries in the coming years (Jianwei Li et al., 2023).

To ensure the safety and reliability of repurposed batteries for secondary applications, comprehensive safety evaluations are essential. These assessments typically involve testing for potential issues such as over-discharging, short circuits, overheating, overcharging, puncturing, and compression, all of which are conducted before evaluating the batteries' performance. reusability. To further enhance battery safety, various assessment techniques, including State of Safety (SOS) evaluations and failure analysis, are employed.

In response to these issues, research is increasingly focusing on sustainable repurposing methods. Evidence indicates that decommissioned LIBs(LIBs) can retain 70-80% of their initial capacity, making them ideal for secondary uses such as renewable energy storage, backup power for homes, and grid stabilization. By implementing organized collection and refurbishment processes, we can significantly extend battery life, minimize electronic waste, and preserve essential materials.

This study introduces an enhanced framework for repurposing LIBs, which emphasizes:

- Efficient Collection & Assessment: Developing effective strategies for the retrieval and evaluation of used LIBs.
- Refurbishment & Alternative Applications: Investigating uses in renewable energy storage and backup power systems.
- Environmental Sustainability & Economic Feasibility: Evaluating the ecological and financial advantages of repurposed LIBs.

By adopting these strategies, this research aims to foster technological advancement while promoting environmental sustainability within the battery sector.

2. Literature Review

[1]Over the past 25 years, lithium-ion battery energy density growth has stagnated at around 3%, and this trend seems to be slowing down. Improvements have been

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gradual due to the complexity of system design and consistent performance across various applications. While breakthroughs don't guarantee immediate commercial success, the global battery market is experiencing rapid growth, driven by surging demand and escalating prices for lithium and cobalt. Initiatives are focused on innovating electrode materials, electrolytes, and separators for emerging technologies. However, sustainability concerns related to LIBs and next-generation rechargeable batteries remain unresolved. Recycling is crucial for battery sustainability, influenced by environmental risks and material value. Therefore, recycling considerations should be integrated into battery system design. While LIB shave revolutionized energy storage, their disposal poses a growing environmental challenge. Initial recycling processes may appear effective, but their long-term effectiveness remains uncertain.

[2][3]Energy Density Trends and Market Growth over the past 25 years, the average rate of increase in energy density for LIBs has been less than 3%, indicating a gradual improvement in battery performance. However, despite these modest improvements, the global battery market is experiencing rapid growth, leading to increased demand and rising prices for critical materials such as lithium and cobalt. (Li, H., 2019; Ciez, R.E., & Whitacre, J.F., 2019; Huo, H., Xing, Y., & Pecht, M., 2017)
[4]Recycling is essential for the sustainability of battery technologies, but its effectiveness is influenced by various factors, including environmental risks and the value of constituent materials. However, current recycling processes often involve the use of toxic chemicals and substantial energy consumption, raising environmental concerns and incurring significant costs. Notably, only 3% of LIBs(LIBs) were recycled in 2019, while 90% of lead-acid batteries were recycled. (Skeete, J.P., et al., 2020).

[5]Advancements in battery components are ongoing, with research and development focused on innovating electrode materials, electrolytes, and separators to meet the demands of emerging technologies like electric vehicles and renewable energy storage. However, sustainability concerns associated with LIBs(LIBs) and next-generation rechargeable batteries have not received adequate attention. (Standridge, C.R., & Corneal, L., 2015; Diekmann, J., Hanisch, C., & Froböse, L., 2017)

[6]Electric vehicle batteries, after approximately ten years of service, may no longer meet the performance standards set for new vehicles. Nevertheless, they retain around 80% of their capacity, making them suitable for repurposing in repurposed applications. (Georgi-Maschler, T., et al., 2012; Karthick, K., et al., 2024) In 2019, the initial cost of a repurposed battery was approximately $50 per kilowatt-hour. However, projections indicate that the cost of new batteries will increase to around $90 per kilowatt-hour by 2025. (Zahoor, A., 2024)

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[7]The paper titled "Sustainable Approaches for Lithium-Ion Battery End-of-Life Management" from the E3S Conference 2025 discusses various strategies for managing end-of-life LIBs, including recycling and repurposing. It emphasizes the environmental benefits of extending battery lifespans and highlights the economic advantages of repurposed applications in reducing the demand for new batteries.

[8] The research paper entitled "Upscaling LIBs for Small-Scale Applications" successfully extends the lifespan of LIBs(LIBs) in small-scale applications. However, the current approach is labour-intensive. This is because large-scale machines are primarily used in the Western market, and we lack the necessary infrastructure. The paper presents a simple and replicable framework that offers promising applications for repurposed batteries, such as power banks and market yard lamps.

3. LIBs Manufacturing Process:

The global lithium-ion battery production rate has been surging exponentially over the past decade, fueled by the surging demand for electric vehicles (EVs), renewable energy systems, and other applications. Here are some key statistics.

The global lithium-ion battery market size was approximately 240 gigawatt-hours (GWh) in 2020. Production capacity is projected to surpass 1 terawatt-hour (TWh) by 2025. Bloomberg NEF predicts a significant increase in lithium-ion production, from 350 GWh in 2020 to 2.3 TWh by 2030.

In terms of specific production rates, some notable manufacturers have reported the following capacities:

- Tesla: Produced over 100 GWh of LIB since 2020.
- Contemporary Amperex Technology (CATL): Reached a production capacity of around 70 GWh in 2020.
- LG Chem: Achieved a production capacity of around 50 GWh in 2020.

It's worth noting that the global lithium-ion battery market is highly competitive, with several other manufacturers also ramping up their production capacities. Notably, Panasonic, Samsung SDI, and BYD are among the prominent players in this market.

The growth in lithium-ion battery production has been driven by various factors:

- Increasing demand for electric vehicles (EVs)
- Growing adoption of renewable energy systems
- Improving technology and manufacturing efficiency
- Decreasing costs

The lithium-ion battery production process involves several stages, from raw material sourcing to final product assembly. Here's an overview of the typical steps involved:

Stage 1: Raw Material Sourcing

- Lithium carbonate (Li_2CO_3) is sourced from mining operations or recycled from spent batteries.
- Graphite and cobalt are also extracted from mines or recycled materials. Other raw materials, such as nickel, manganese, and iron, may be added to the cathode mixture.

Stage 2: Cathode Material Production

- Lithium carbonate is converted into lithium hydroxide (LiOH) through a chemical reaction.
- The lithium hydroxide is then mixed with other ingredients, such as graphite, cobalt, nickel, manganese, and iron, to create the cathode material.

Stage 3: Anode Material Production

- Graphite is purified and processed into anode material.
- Other materials, such as silicon or tin, may be added to enhance the anode's performance.

Stage 4: Electrolyte Production

- The electrolyte is a liquid or gel-like substance that enables the transport of ions between the cathode and anode. Common electrolytes include lithium hexafluorophosphate ($LiPF_6$), which is typically dissolved in a mixture of organic solvents such as ethylene carbonate (EC), diethyl carbonate (DEC), and dimethyl carbonate (DMC).

Stage 5: Cell Assembly

- The cathode and anode materials are cut into thin sheets and assembled into individual cells using a pressing machine.
- The electrolyte is injected into the cell through a small opening, which is then sealed.

Stage 6: Cell Testing and Sorting

- Cells are tested for their electrical performance, including voltage, capacity, and internal resistance.
- Defective cells are sorted out and recycled or disposed of properly.

Stage 7: Module Assembly

- Multiple cells are interconnected in series and parallel to form a module, which serves as the fundamental building block of a battery pack.
- Modules can be further organized into larger modules or even entire battery packs.

Stage 8: Battery Pack Assembly

- The final stage involves assembling the individual modules into a complete battery pack.
- This includes adding external components, such as connectors, circuit boards, and enclosures.

Stage 9: Final Testing and Quality Control

- Complete battery packs undergo rigorous testing to ensure they meet quality and performance standards.
- Batteries are inspected for defects, and any issues are addressed through repairs or replacements.

Stage 10: Packaging and Shipping

- Battery packs are packaged and prepared for shipping to customers.
- Safety precautions, such as labelling and packaging instructions, are included to ensure safe handling and use.

This is a simplified overview of the lithium-ion battery production process. Actual manufacturing processes may vary depending on the specific company or facility.

4. Impacts of Lithium-Ion Batteries:

The production and usage of lithium-ion (Li-ion) batteries have several environmental impacts, including:

Production Impacts:
1. Resource Extraction: Lithium, cobalt, nickel, and other metals utilized in lithium-ion battery production are frequently extracted employing environmentally detrimental methods, such as open-pit mining.
2. Energy Consumption: The production of LIBs necessitates substantial energy consumption, which is often sourced from non-renewable sources like coal or natural gas.
3. Water Usage: Lithium extraction and processing entail substantial water consumption, which can strain local water resources and adversely impact ecosystems.

4. Waste Generation: Lithium-ion battery manufacturing generates waste materials, including lithium-rich waste, which poses hazardous risks if not disposed of appropriately.

Example: A 2020 study conducted by the Swedish Environmental Research Institute revealed that the manufacturing phase of a single Tesla Model S electric vehicle emits approximately 25 tons of CO_2 equivalent emissions. This significant portion of emissions is attributed to the extraction and processing of materials such as lithium, cobalt, and nickel.

Usage Impacts:

1. Charging energy consumption: Charging Li-ion batteries requires energy, which can lead to increased greenhouse gas emissions from power plants.
2. Battery degradation: Over time, Li-ion batteries degrade, leading to reduced performance and eventually requiring replacement. This generates more waste and contributes to the demand for new materials.
3. End-of-life disposal: The disposal of spent Li-ion batteries poses environmental concerns due to their potential toxicity and the risk of fires or explosions during transportation.

Example:

A study conducted by the University of California, Berkeley, projected that if all light-duty vehicles in the United States were transitioned to electric vehicles (EVs) by the year 2050, the cumulative demand for lithium would approximately reach 12 million tons. This substantial requirement would necessitate extensive mining, processing, and refining operations, potentially resulting in adverse environmental consequences and societal impacts.

Environmental Concerns:

1. Lithium Mining Impact on Ecosystems: Lithium mining can have detrimental effects on local ecosystems, including water pollution, soil degradation, and biodiversity loss.
2. Cobalt Sourcing Challenges: Cobalt is frequently extracted from artisanal mines in countries such as the Democratic Republic of Congo (DRC), where child labour and human rights concerns are significant.
3. Battery Recycling Challenges: The recycling of LIBs remains in its early stages, and current methods can be energy-intensive and generate hazardous waste.

5. Conclusion and Future Work

Efforts to Mitigate Environmental Impacts:

1. Sustainable mining practices: Some companies are adopting more sustainable mining practices, such as using renewable energy or reducing water usage.
2. Recycling innovations: Researchers are developing new recycling technologies that can recover valuable materials from spent batteries with minimal environmental impact.
3. Battery design improvements: Manufacturers are designing batteries with recyclability in mind, using fewer and more abundant materials, and improving overall efficiency.

Recommendations:

1. Increase recycling rates: Encourage the development of efficient battery recycling technologies to minimize waste generation.
2. Promote sustainable mining practices: Support companies adopting environmentally responsible mining practices and advocate for improved regulations.
3. Design for recyclability: Encourage manufacturers to design batteries with recyclability in mind, using fewer and more abundant materials.

Sustainable repurposing of LIBs presents a viable solution to mitigate environmental challenges while addressing the rising demand for energy storage. By refining collection, grading, and refurbishment techniques, LIBs can be efficiently repurposed to extend their usability.

[8] In this paper, the author delves into the feasibility and market potential of extending the lifespan of batteries, providing valuable insights into this field. In response to the opportunities identified in repurposing and reusing lithium-ion batteries, a startup called “Becoba Energy Private India Limited” has been established. While this type of repurposing is quite common in Western countries like the USA, UK, and not so prevalent in our country, there is a significant need for awareness and understanding of sustainable practices for recycling and safe disposal of lithium-ion batteries.

Online Sources

1. International Energy Agency (IEA): "Electric Vehicles: Past, Present and Future"
2. Bloomberg NEF: "New Energy Outlook 2020"

3. European Environment Agency (EEA): "Lithium-ion battery production and recycling"
4. World Bank: "Artisanal and Small-Scale Mining in the Democratic Republic of Congo"

References

1. Zahoor et al., "Urgent Needs for Repurposed Battery Recycling," Environmental Science and Pollution Research, 2024.
2. M. DeRousseau et al., "Repurposing Used Electric Car Batteries: A Review of Options," JOM, 2017.
3. J. Diekmann et al., "Ecological Recycling of Lithium-Ion Batteries," J. Electrochem. Soc., 2017.
4. L. Gaines et al., "Life-Cycle Analysis of Lithium-Ion Battery Production and Recycling," Transportation Research Board, 2011.
5. B. Nykvist & M. Nilsson, "The Evolution of Lithium-Ion Battery Costs and Implications for Repurposed Applications," Nature Energy, 2015.
6. S. Georgi-Maschler et al., "Aging Mechanisms and Performance of LIBsfor Repurposed Use," Applied Energy, 2012.
7. E3S Conference Paper, "Advancements in LIB Sustainability," E3S Conferences, 2025.
8. Sah, P. V., Adithya, N. N. S. S. S., Priya, K. P., & Indira, D. (2025). Upscaling LIBsfor Small Scale Applications. In *E3S Web of Conferences* (Vol. 619, p. 01002). EDP Sciences.
9. Heelan, J. Gratz, E. Zheng, Z., (2016). Current and prospective Li-Ion battery recycling and recovery processes. JOM. 2016; 68:2632-2638
10. Hong Li, (2019), Practical Evaluation of Li-Ion Batteries, Joule, Volume 3, Issue 4, 17 April 2019, 911-914.
11. Huo, H. Xing, Y. Pecht, M., (2017). Safety requirements for transportation of lithium batteries, Energies. 2017; 10:793
12. Jean-Paul Skeetea, Peter Wellsa , Xue Donga , Oliver Heidrichb , Gavin Harperc, (2020), Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition, Energy Research & Social Science, 69 (2020) 1015.
13. Jianwei Li, Shucheng He, Qingqing Yang, Zhongbao Wei, Yang Li, and Hongwen He, (2023). A Comprehensive Review of Second Life Batteries Toward Sustainable Mechanisms: Potential, Challenges, and Future Prospects, IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, VOL. 9, NO. 4, DECEMBER 2023.
14. Juner Zhu, (2021). End-of-life or repurposed options for retired electric vehicle batteries, Cell Reports Physical Science 2, 100537, August 18, 2021.
15. Md. Tanjil Sarker, Mohammed Hussein Saleh Mohammed Haram, Siow Jat Shern, Gobbi Ramasamy and Fahmid Al Farid (2024). Repurposed Electric Vehicle Batteries for Home Photovoltaic Systems: Transforming Energy Storage and Sustainability, Energies 2024, 17(10), 2345.