Implementation of Large-Scale Electric Vehicle Battery Recycling

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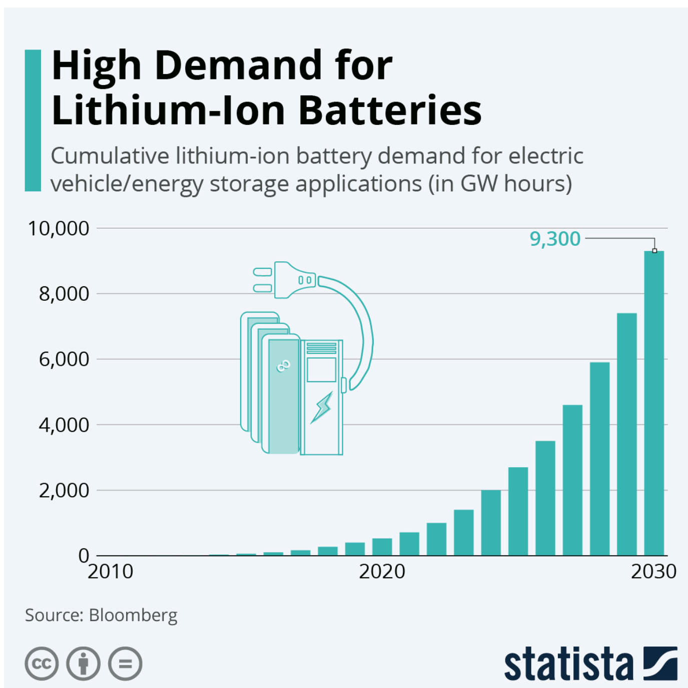
Introduction:

The accelerating adoption of electric vehicles (EVs) represents a critical step towards reducing carbon emissions and fostering sustainable transportation systems worldwide. Global EV sales have surged, with an increase of approximately 43% between 2020 and 2022 alone, and projections suggest that EVs could make up nearly 30% of all new vehicle sales by 2030 (International Energy Agency, 2022). However, the rapid growth in EV use introduces pressing challenges regarding the sustainable management of end-of-life lithium-ion batteries (LIBs). These batteries, with an estimated lifespan of 8–15 years, are expected to accumulate in significant volumes within the coming decade, posing environmental risks and resource scarcity concerns. Proper disposal and recycling of LIBs are critical due to their content of valuable metals such as lithium, cobalt, and nickel, which are not only finite in supply but environmentally intensive to extract.



Graph showing the actual and predicted growth of LIB demand

Existing research underscores the need for advancements in EV battery recycling. Studies highlight the environmental hazards posed by improper disposal of EV batteries, including potential soil and water contamination (Harper et al., 2019). Additionally, recent assessments of the current recycling technologies, such as pyrometallurgical and hydrometallurgical processes, reveal both strengths and limitations(Xu et al., 2020; Ciez & Whitacre, 2019, Gaines, 2018, Harper et al., 2019). While these processes are effective in recovering certain high-value metals, they are often energy-intensive and produce significant waste by-products, limiting their sustainability (Gaines, 2018). As the EV market continues to grow, these methods alone are insufficient to manage the projected volume of end-of-life batteries effectively. Furthermore, the economic feasibility of large-scale recycling remains underexplored, particularly in understanding the cost-benefit trade-offs associated with various recycling techniques (Kallitsis et al., 2020). These findings point to a pressing need for regionally tailored, scalable, economically viable, and environmentally friendly LIB recycling solutions—gaps that this research aims to fill.

Aiming to address this need, the proposed research asks the question: **How can regional policies and geographic knowledge inform LIB recycling strategies to overcome current challenges in LIB recycling in the United States?** Drawing on existing literature, global case studies, and regional analysis of factors impacting LIB recycling, this study will identify effective policy-driven approaches and geographic insights that could support scalable recycling solutions in diverse contexts.

The broader impacts of this research are significant, both practically and theoretically. Environmentally, the study seeks to reduce dependency on primary resource extraction, a key driver of ecological degradation and carbon emissions. Recycling EV batteries not only conserves critical materials but also mitigates pollution risks associated with landfill disposal. Economically, this research could contribute to job creation in the growing green technology sector, particularly in battery refurbishment and materials recovery, providing new economic opportunities in regions affected by industrial decline. Additionally, this work aligns with and supports policy initiatives around Extended Producer Responsibility (EPR) (Baars et al., 2021), offering policymakers data-driven recommendations for structuring efficient recycling programs and legislation to support sustainable infrastructure.

From a theoretical perspective, this research will enhance our understanding of how circular economy principles apply to high-tech industries. By investigating the challenges and opportunities associated with recycling lithium-ion batteries (LIB), we can gain insights into the transition from linear to circular economic models in technology-driven sectors. This study will contribute to our knowledge of industrial ecology by illustrating how waste from one industry, such as the automotive sector, can be transformed into valuable resources for others, thereby reshaping our understanding of resource flows and industrial collaboration.

This research will also examine how geographic factors influence the effectiveness of large-scale lithium-ion battery recycling initiatives in the United States, utilizing the following methods: a literature review, case studies of industry leaders like Redwood Materials, and interviews with recycling facility workers. The literature review explores recycling technologies, economic viability, and environmental impacts, highlighting how regional variations in infrastructure and energy sources affect recycling efficiency. Case studies will analyze the roles of regional policies and market dynamics, while interviews will provide insights into operational challenges shaped by local contexts. This methodology offers a nuanced understanding of how regional characteristics, such as electric vehicle adoption and the distribution of recycling centers, interact with local economic conditions to impact recycling success and policies. This geographic perspective will provide valuable insights into effectively implementing sustainable technologies in various local and regional contexts.

Ultimately, this research addresses a critical gap in sustainable technology by developing an evidence-based framework for large-scale EV battery recycling in the United States. By examining how geographic factors—such as regional EV adoption patterns, the location of recycling infrastructure, transportation logistics, and local policy variations—affect the feasibility and effectiveness of recycling programs, this study contributes uniquely to the geographic dimension of sustainable technology. This approach aims to reveal how location-specific factors influence the environmental impact of recycling initiatives and their economic and logistical viability.

The study's findings are expected to advance knowledge in material science, environmental policy, green technology, and economic geography. Through a regional lens, it contributes directly to realizing a circular economy in transportation by showing how geographic knowledge can inform optimal recycling strategies, reduce transportation-related emissions, and align recycling operations with local needs and conditions. By establishing practical, scalable recycling solutions and analyzing their spatial implications, this research not only supports the transition to cleaner transportation but also lays the groundwork for a sustainable, resource-efficient future that is adaptable to the diverse geographic and policy landscapes across the United States.

Background:

Current Knowledge and Gaps

The global transition to electric vehicles (EVs) has significantly increased demand for lithium-ion batteries (LIBs) while creating environmental and resource challenges from accumulating end-of-life LIBs. Studies have analyzed recycling methods, focusing on pyrometallurgical, hydrometallurgical, and direct recycling, to recover materials like lithium, cobalt, and nickel (Harper et al., 2019). Pyrometallurgy, despite being well-established, produces low-purity by-products and has high energy demands and emissions, limiting its sustainability (Gaines, 2018). Hydrometallurgy offers higher material purity and lower energy consumption but faces scalability issues and generates chemical waste requiring careful management (Xu et al., 2020; Ciez & Whitacre, 2019). Direct recycling, which preserves intact cathode and anode materials, could maintain the electrochemical performance of recycled components (Mossali et al., 2020). However, technical barriers, such as disassembly complexity and variations in LIB chemistries, limit its efficiency and scalability, with no commercial-scale application to date (Mossali et al., 2020; Mayyas et al., 2019).

Visual representation of LIB recycling processes, Source: Wang, Xiao-Tong et al. (2022)

Geographic factors further influence the feasibility and sustainability of LIB recycling. Urban areas with high EV adoption benefit from nearby recycling facilities that lower transportation costs and emissions, while rural regions face logistical challenges due to infrastructure gaps. Gregson et al. (2015) highlight how such "geographies of waste" create spatial inequalities in access to recycling systems, impacting access to recycling systems, and shaping material flows and management. Inconsistent regional policies also hinder the scalability of circular economy initiatives, particularly in standardizing waste classification and transport regulations (McDowall et al., 2017). Labor geographies reveal further disparities because they often perpetuate existing inequalities. Advanced recycling facilities are concentrated in the Global North and labor-intensive operations are relegated to less-regulated regions, highlighting critical environmental and social justice concerns (Pansera et al., 2024). This research addresses these spatial variations, exploring how EV adoption, renewable energy resources, and recycling facility distribution affect LIB recycling scalability, contributing to a better understanding of geographic barriers and opportunities in achieving circular economy goals.

Unresolved Issues and Limitations

While substantial advancements have been made in recycling techniques, significant gaps remain in the economic, environmental, and technical feasibility of large-scale LIB recycling. Economic analyses, such as those by Steward et al. (2019) and Zhao et al. (2024), reveal that LIB recycling operations often struggle to compete with the cost of primary material extraction, primarily due to high logistical costs associated with battery collection, sorting, and transportation. Additionally, the decentralized and fragmented nature of recycling facilities creates inefficiencies in material recovery rates and incurs significant transportation emissions, raising concerns about the overall environmental footprint of the recycling process (Borah et al., 2024). Compounding these issues, battery manufacturers employ various cell designs and chemistries, complicating disassembly and material recovery. This diversity in battery composition not only limits the effectiveness of current recycling methods but also increases the need for adaptable processes capable of handling a wide range of LIB types (Wang et al., 2024).

From an environmental perspective, studies point to the ecological costs of energy-intensive recycling methods, particularly pyrometallurgy, which generates substantial greenhouse gas emissions and hazardous by-products (Wang et al., 2014). Although hydrometallurgy presents a lower-energy alternative, it requires substantial quantities of reagents, which must be carefully managed to avoid toxic waste generation (Ciez & Whitacre, 2019). Efforts to improve environmental outcomes in LIB recycling have shown that direct recycling and advanced sorting technologies could yield more sustainable results, but these methods are not yet mature enough for industrial-scale deployment due to technical limitations in separating and preserving specific battery materials. These challenges highlight the urgent need for optimized recycling methods that balance economic and environmental considerations and can be scaled to meet the rising volume of end-of-life LIBs as the EV market expands (Xu et al., 2020; Gaines, 2018). By incorporating geographic knowledge, this study aims to identify strategies for optimizing recycling networks to balance economic, environmental, and technical considerations while responding to the localized needs of diverse regions.

Study Relevance and Contribution to the Field

Addressing the identified limitations is crucial for advancing sustainable EV battery management and establishing a resilient supply chain for critical raw materials. My research aims to fill these critical gaps by creating an integrated recycling approach that combines the strengths of hydrometallurgical and direct recycling methods to maximize material recovery efficiency and minimize environmental impact. This approach will also assess the feasibility of implementing closed-loop systems within the battery recycling sector, which could significantly reduce dependency on primary raw material extraction and help stabilize the supply of key metals like cobalt and nickel (Harper et al., 2019; Baars et al., 2021). The research builds upon foundational work in LIB recycling by proposing scalable solutions for the selective recovery of high-purity LIB materials. By addressing the technical barriers of direct recycling and optimizing material processing techniques, this study contributes to advancing the field toward practical applications that are not only sustainable but economically viable.

From a geographic perspective, this study examines how regional variations in infrastructure, policy frameworks, and market dynamics shape the economic and environmental feasibility of lithium-ion battery (LIB) recycling systems, contributing to debates in environmental and economic geography on resource management and industrial sustainability. By investigating spatial dimensions of circular economy practices, it highlights the influence of location-specific factors such as renewable energy availability, proximity to EV markets, and differing regulatory environments on recycling outcomes. This research emphasizes the importance of geographically adaptive strategies that address these variations to improve recycling efficiency and scalability. By advancing knowledge on the economic potential and practical implementation of tailored hybrid recycling methods, the study supports the transition toward a sustainable, circular battery lifecycle. These insights offer critical guidance for designing regionally appropriate policies that leverage local capacities while contributing to global sustainability efforts and addressing resource scarcity in the EV sector (Pagliaro & Meneguzzo, 2019; Zhao et al., 2024).

The study’s interdisciplinary approach bridges technical and geographic knowledge, providing a comprehensive framework for understanding LIB recycling’s challenges and opportunities. Technically, it informs scalable recycling practices, while geographically, it enhances understanding of spatial inequalities and policy implications in resource management. Together, these contributions provide actionable insights for policymakers and industry leaders to promote a circular economy, addressing both the technical feasibility and spatial complexities of sustainable EV battery recycling.

Conceptual Framework

This study is underpinned by the principles of the circular economy, which emphasize the minimization of waste and the continuous reuse of resources to extend product lifecycles. The circular economy model advocates for “closed-loop” systems where materials are recovered and reintegrated into production processes, reducing the demand for virgin materials and decreasing environmental impact (European Parliament, 2023). Applying this framework to LIB recycling underscores the necessity of efficient material recovery processes that can maintain the quality and performance of recycled components, an area where current recycling approaches fall short. Research from Baars et al. (2021) and the U.S. Department of Energy (2021) emphasizes that a successful circular economy for LIBs must not only enhance recycling methods but also implement design-for-recycling principles to facilitate easier disassembly and material recovery.

However, achieving these goals requires a geographic perspective to address disparities in the distribution of resources, infrastructure, and policy support. Pickren (2018) critiques how existing e-waste recycling programs often overlook regional differences in technological, regulatory, and socio-economic contexts, creating a disconnect between "ethical" recycling models and on-the-ground realities. A geographic lens enriches the circular economy framework by illuminating how regional contexts influence recycling outcomes. Drawing on concepts from political ecology, this study explores how power dynamics and resource flows determine access to recycling technologies and sustainable practices. Robbins (2012) underscores the critical need to examine the intersection of local and global processes in shaping uneven development in resource management. Applying this perspective to LIB recycling reveals how spatial and socio-political disparities impact the implementation of circular economy principles, offering a nuanced understanding of the challenges and opportunities for sustainable recycling practices.

This study bridges the gap between recycling practices and circular economy objectives with the help of geographic perspectives. It offers regionally adaptive solutions to challenges like economic viability, standardization, and sustainability, contributing to scalable, sustainable recycling systems that account for the spatial and socio-political complexities of global LIB recycling.

Methods:

Research Methods Plan and Justification

This study adopts a multi-method approach to examine the feasibility, challenges, and strategies for implementing large-scale electric vehicle (EV) battery recycling, focusing on both industrial and geographical factors. By combining a comprehensive literature review, case studies of leading industry players across diverse locations, and firsthand interviews with facility workers, this methodology provides a holistic view of the technical, economic, and environmental aspects of EV battery recycling. This integrated approach enables a geographically aware analysis of recycling practices, addressing not only the economic and operational dynamics but also the spatial and regulatory variations influencing EV battery recycling across different regions.

1. Comprehensive Literature Review: The literature review will establish the theoretical foundation of this research, covering:
    a. Recycling Technologies: Analyzing pyrometallurgical, hydrometallurgical, and direct recycling methods to understand their varying efficiencies, environmental impacts, and suitability for different locations based on infrastructure availability and energy costs.
    b. Economic Viability: Examining studies on material recovery rates, processing costs, and market dynamics to assess the economic potential of recycling compared to primary extraction. This section will focus on how market conditions and regulatory incentives differ by region, influencing the profitability and scalability of recycling operations.
    c. Environmental Impact: Evaluating the environmental implications of battery recycling across different stages of the EV battery lifecycle, considering how regional factors like energy sources and waste management policies impact recycling's potential to reduce reliance on primary resources.

Data for the literature review will be gathered from peer-reviewed academic databases, such as ScienceDirect, Google Scholar, and IEEE Xplore, and industry publications from organizations like Benchmark Mineral Intelligence and Circular Energy Storage. Additionally, government reports from entities like the International Energy Agency (IEA), the European Union, and the U.S. Department of Energy will provide insight into policy frameworks and global trends, supporting a geographically nuanced understanding of the regulatory landscapes influencing recycling practices.

2. Case Studies of Key Industry Players: The case study phase will focus on five companies, each representing a unique aspect of the EV battery recycling industry, to explore how geographic factors shape recycling practices. Selected companies are located in regions with varying market dynamics, regulatory environments, and access to infrastructure, allowing for a comparative analysis of recycling strategies across different geographical contexts.
    a. Redwood Materials (United States): Located in Nevada, Redwood Materials emphasizes creating a closed-loop supply chain, leveraging Nevada's logistical advantages and regulatory support for green technologies. This case offers insights into recycling operations within a U.S. regulatory context that encourages circular economy initiatives.
    b. American Manganese Inc. (Canada): Based in British Columbia, American Manganese Inc. specializes in its proprietary RecycLiCo™ technology. Canada's emphasis on sustainable resource management and recycling incentives provides a context to examine the effectiveness of advanced recycling technologies in a supportive regulatory framework.
    c. Glencore (Switzerland): A major player in metals and mining with recycling facilities across Europe, Glencore illustrates how established resource companies adapt to recycling demands, benefiting from the European Union's robust recycling policies and incentives.
    d. Li-Cycle Corp. (Canada): Headquartered in Toronto with facilities across North America, Li-Cycle is recognized for its innovative business models and technology, reflecting North America's growing interest in sustainable practices amid varied regional regulations.
    e. Neometals Ltd. (Australia): Operating in Perth, Neometals focuses on proprietary hydrometallurgical processes. This case highlights the challenges and opportunities of recycling in regions with limited recycling infrastructure but strong resource management policies.

Each company's geographical context influences its recycling approach, shaped by factors such as local regulatory incentives, resource availability, and market conditions. This analysis will also consider whether the regulatory frameworks impacting the company stem from its headquarters location, the specific locations of its recycling facilities, or a combination of both, as these distinctions can significantly affect operational strategies and compliance requirements. This geographically aware selection allows for an analysis of how location impacts recycling strategies, regulatory compliance, and operational sustainability. Data for these case studies will be sourced from corporate reports, financial disclosures, environmental impact assessments, technical presentations, and patent filings. Sources include company websites, regulatory filings on databases like EDGAR (for U.S.-based companies) and SEDAR (for Canadian companies), as well as industry publications and databases such as Bloomberg and Reuters for financial information. This variety of data sources supports a comprehensive, multi-dimensional analysis of each company's recycling practices, technological advancements, and financial viability.

3. Interviews with Facility Workers: To gain operational insights into large-scale EV battery recycling, this study will conduct approximately 10-15 interviews with workers from selected recycling facilities, focusing on specific sites rather than the broader company to capture facility-specific practices and challenges. These facilities have been chosen to provide diverse perspectives across geographical and organizational contexts. These interviews aim to:
    a. Understand day-to-day challenges, such as handling different battery chemistries, managing environmental waste, and ensuring safety.
    b. Capture the impact of location-specific regulations on operational practices and workflow.
    c. Identify potential areas for improvement in technology, workflow, and resource utilization based on worker insights.

This sample size is justified as it provides a broad yet manageable range of perspectives, balancing depth and coverage across facilities while allowing for a detailed thematic analysis. Interviews will be conducted via Zoom video conferencing or in person, depending on the participant's location and preference, and will follow a semi-structured format to capture both specific operational details and broader experiences. Interviews will be arranged by contacting HR departments for permission, attending industry events, and reaching out through LinkedIn. This approach ensures a diverse sample, representing multiple levels within the facilities, from operators to managers, thus capturing a full spectrum of operational insights.

Data Analysis

The data analysis will employ both qualitative and quantitative methods to comprehensively evaluate the operational, economic, and environmental aspects of EV battery recycling across different contexts.

1. Qualitative Analysis: Thematic analysis will be conducted on interview transcripts and case study data using NVivo software, allowing for a detailed examination of recurring themes, such as operational challenges, regulatory impacts, and technological constraints. Key themes will include:
    a. Technical Feasibility: Comparing the effectiveness and adaptability of different recycling technologies within diverse regulatory and market environments.
    b. Operational Challenges: Identifying common challenges reported by workers and analyzing how geographical factors influence these challenges.
    c. Environmental and Economic Outcomes: Assessing the perceived environmental and financial impact of recycling operations, particularly how regional policies support or hinder sustainable practices.

2. Quantitative Analysis: This study will prioritize facility-level metrics such as material recovery rates, energy consumption, and processing costs, sourced from environmental impact assessments, technical reports, and site-specific disclosures in sustainability reports. Interviews with facility managers and staff will provide additional data unavailable in public records. Where facility-level data is unavailable, aggregated financial metrics like revenue from recovered materials and processing costs will be drawn from corporate filings (e.g., SEC filings) and databases such as CapitalIQ and Bloomberg. These figures will be contextualized with qualitative insights from case studies and interviews to ensure the analysis reflects localized realities rather than generalized trends. Using SPSS, the study will conduct exploratory analysis and descriptive statistics to uncover patterns and relationships among key variables. The analysis will focus on:
    a. Quantitative data on recovery rates will be examined with facility locations, accounting for regional regulations, proximity to renewable energy sources, and local infrastructure to assess the environmental performance of recycling across different regions.
    b. Facility-level processing costs, including regulatory compliance expenses and logistical costs, will be analyzed to evaluate their impact on profitability. This will

involve comparing facilities in regions with high regulatory stringency against those in less-regulated areas.

c. Revenue data for recovered materials will be analyzed alongside regional demand and supply chain structures to understand how market conditions influence the economic feasibility of recycling operations.

The analysis will also incorporate facility-specific qualitative insights to contextualize the quantitative findings, ensuring that results reflect operational realities rather than speculative assumptions. This geographically informed approach will highlight disparities across regions, providing a nuanced understanding of how location-specific factors shape recycling practices and sustainability outcomes.

Data Management

1. Data Collection and Sources: Data sources include peer-reviewed articles, industry reports, and government publications for the literature review, alongside company reports and financial disclosures for case studies. Interview data will complement these sources by providing operational insights.
2. Data Security and Storage: Digital data, including transcripts and case study documents, will be stored on an encrypted external drive with a secure cloud backup. Access to data will be restricted to the primary researcher. Physical documents will be stored in a locked filing cabinet.
3. Data Analysis and Retention: Qualitative data will be analyzed in NVivo, while quantitative data will be processed in SPSS to explore relationships between operational efficiency, geographical context, and regulatory factors. Data will be retained for five years before secure deletion, with periodic reviews of security protocols to ensure compliance with GDPR and evolving data protection standards.

Ethics

This research will strictly adhere to ethical guidelines, ensuring that participant rights, privacy, and autonomy are respected.

1. Informed Consent and IRB Approval: Institutional Review Board (IRB) approval will be obtained prior to conducting interviews, verifying that all procedures comply with ethical standards. In addition, HR departments of each company will be contacted to secure permission for employee participation, ensuring adherence to company policies.

2. Participant Information and Voluntary Participation: Participants will be fully informed of the study's objectives, procedures, and data use, with an emphasis on their right to withdraw at any time. Interview candidates will receive clear explanations of the interview process and assurances that their responses will be anonymized.
3. Confidentiality and Data Security: All collected data will be anonymized and stored securely to comply with GDPR regulations. Audio recordings will be transcribed locally using secure software, with recordings deleted after verification. Transcripts will be securely stored on encrypted, password-protected drives, with physical documents such as consent forms kept in a locked cabinet. Conflicts of interest will be disclosed in any resulting publications or presentations.

Anticipated Impacts:

This research aims to make significant contributions to policy, industry practices, and academic knowledge in the field of sustainable EV battery recycling. By examining the geographic and contextual factors shaping the viability of recycling systems, this study will provide actionable insights for policymakers to design regionally adaptive regulations that support the adoption of efficient and environmentally sustainable recycling technologies. For example, findings could inform the development of localized policies that align recycling technology selection with regional energy sources and regulatory frameworks, ensuring compatibility with local environmental and economic goals.

In the recycling industry, this research will offer guidance on best practices for overcoming operational challenges, such as managing diverse battery chemistries and optimizing material recovery processes. Industry stakeholders can use these insights to enhance the scalability and profitability of recycling initiatives while improving environmental performance. Furthermore, the geographically informed analysis will highlight disparities in infrastructure and policy environments, encouraging investment in regions with untapped recycling potential and fostering more equitable access to sustainable practices.

This study also contributes to public awareness and educational efforts by demonstrating the importance of circular economy principles and the role of geography in shaping sustainability outcomes. By illustrating how regional variations impact recycling systems, the research will help advocate for more localized, inclusive approaches to resource management.

Academically, this work advances knowledge in economic and environmental geography, providing a geographically nuanced perspective on circular economy transitions. Regardless of specific findings, the research emphasizes the need for place-specific strategies to address global sustainability challenges, contributing to ongoing debates on resource management and sustainable industrial practices. These broader impacts will inform future policy development, industry innovations, and public engagement, promoting a more sustainable and circular approach to managing end-of-life EV batteries.

Conclusion:

This research aims to advance the understanding of large-scale EV battery recycling by exploring the intersection of recycling technology, economic feasibility, environmental impact, and geographic context. By combining a detailed literature review with case studies and interviews across diverse geographical locations, the study provides a comprehensive analysis of how regional factors shape the sustainability and scalability of battery recycling practices.

The expected findings will inform industry stakeholders, policymakers, and researchers about the most effective recycling technologies and economic models suited to various regional contexts. Moreover, the study will emphasize the critical role of localized policies and incentives in fostering a sustainable battery recycling industry. The geographic insights generated from this research will contribute to broader debates on circular economy practices and resource management, offering a foundation for developing strategies that align economic and environmental objectives with the unique characteristics of each region.

Ultimately, this research seeks to bridge the knowledge gap in EV battery recycling by identifying pathways to economically viable and environmentally sustainable recycling solutions. The outcomes will not only guide the EV industry in its transition to a circular economy model but also support broader sustainability goals by promoting resource conservation, reducing reliance on primary raw materials, and minimizing the environmental footprint of the EV battery lifecycle. This geographically informed approach positions the study as a critical step toward advancing sustainable resource management within the context of the global shift toward electric mobility.

Timeline:

- Month 1-2: Project Planning and Initial Literature Review
  - Weeks 1-2: Finalize research objectives, refine methodology, and create a detailed project plan.

- Weeks 3-8: Begin a comprehensive literature review on EV battery recycling technologies, economic factors, and environmental impacts across different geographic contexts.
- End of Month 2: Complete an initial summary of existing research and identify specific gaps to address in case studies and interviews.

- Month 3: Ethics and Institutional Approvals
  - Weeks 9-10: Submit research proposal to the Institutional Review Board (IRB) for ethical approval of interviews.
  - Weeks 11-12: Reach out to the HR departments of selected companies (Redwood Materials, American Manganese Inc., Glencore, Li-Cycle Corp., Neometals Ltd.) to gain permission for employee interviews and request necessary access for case study data.

- Month 4-5: Literature Review Completion and Document Collection for Case Studies
  - Weeks 13-20: Continue literature review, focusing on identifying key themes and synthesizing geographic and environmental implications in EV battery recycling.
  - Collect necessary documents for case studies, including company reports, regulatory filings, environmental assessments, and industry publications.
  - End of Month 5: Finalize the literature review and begin structuring findings related to regional and technological variations.

- Month 6-7: Case Study Data Collection and Preliminary Analysis
  - Analyze company-specific data from the selected case study companies, with a focus on technical, economic, and regulatory aspects.
  - Begin preliminary analysis of how geographical factors impact recycling strategies across different companies and regions.

- Month 8-9: Conduct Interviews and Complete Data Collection
  - Conduct 10-15 semi-structured interviews with facility workers and industry professionals at the selected companies. Schedule both virtual and in-person interviews as appropriate, ensuring geographic diversity.
  - Transcribe interviews and begin categorizing qualitative data based on operational, environmental, and regional themes.

- Month 10: Data Analysis
    - Conduct thematic analysis of qualitative data from interviews using NVivo to identify recurring themes and insights.
    - Perform quantitative analysis on case study data using SPSS, examining correlations between geographic factors (e.g., energy sources, regulations) and economic or environmental outcomes in recycling.
    - Integrate qualitative and quantitative findings to draw conclusions about geographic implications for battery recycling practices.

- Month 11: Writing and Synthesis of Findings
    - Weeks 41-44: Begin writing the results and discussion sections, emphasizing the geographic significance of findings and how they contribute to debates in environmental and economic geography.
    - Weeks 45-46: Draft the introduction, methods, and anticipated results sections based on analysis and initial conclusions.

- Month 12: Revisions and Finalization
    - Weeks 47-50: Revise and refine the full draft based on feedback from advisors or peers and ensure all references, citations, and data management practices comply with ethical guidelines.
    - Weeks 51-52: Final proofreading and formatting. Submit the completed research report or proposal.

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