# Supply Chain Management for Electric Vehicles: Challenges, Opportunities, and the Path to Scalability

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***Abstract*****—**As electric vehicles (EVs) gain momentum as a solution to reduce greenhouse gas emissions and fossil fuel dependence, their supply chains become increasingly complex, particularly for lithium-ion batteries (LIBs), which are crucial for EV performance, safety, and longevity. This paper reviews existing literature on several key aspects of the EV supply chain, focusing on thermal management systems (TMS), lifecycle environmental assessments, closed-loop supply chains (CLSCs), and the impacts of global disruptions like the COVID-19 pandemic. Research by Murugan et al. (2022) underscores the importance of improving TMS for LIBs, noting that experimental validation remains sparse despite advances in numerical modeling. In addition, Rüdisüli et al. (2022) highlight the environmental benefits and limitations of different mobility technologies, emphasizing the need for advancements in seasonal energy storage systems. Gu et al. (2018) discuss the challenges of establishing profitable CLSCs for EV batteries, where reuse improves sustainability, but recycling faces economic hurdles. Finally, the analysis of Wen et al. (2021) on the COVID-19 pandemic's impact shows significant disruptions to the Chinese EV market and raises concerns about the global EV supply chain's resilience. This review identifies gaps in the literature, such as the need for real-world validation of models, exploration of alternative battery chemistries, and improved supply chain governance, all of which are essential for advancing the EV industry toward sustainability.

*Keywords—Electric Vehicles, Supply Chain Management, Lithium-ion Batteries, Thermal Management Systems, Closed-Loop Supply Chains, Sustainability, Greenhouse Gas Emissions, Lifecycle Assessment, Resource Dependencies, Circular Economy.*

## I. INTRODUCTION

Electric vehicles (EVs) have become a cornerstone of the global push toward sustainability, driven by the need to reduce greenhouse gas emissions and dependence on fossil fuels. As the demand for EVs grows, so does the complexity of the supply chains that support their production and operation. In particular, lithium-ion batteries (LIBs), a critical component in EVs, present unique challenges due to their role in determining vehicle performance, safety, and longevity. The management of thermal conditions in LIBs, often called the thermal management system (TMS), has emerged as a focal point in ensuring battery reliability. However, despite significant advances in numerical modeling, experimental validation remains limited, which has led to calls for further exploration of alternative battery chemistries and increased international collaboration (Murugan et al., 2022).

Another critical aspect of EV sustainability is understanding the environmental implications of various mobility technologies. Researchers like Rüdisüli et al. (2022) have examined the lifecycle greenhouse gas (GHG) emissions associated with battery electric vehicles (BEVs), hydrogen fuel cell electric vehicles (H2-FCEVs), and synthetic natural gas vehicles (SNG-Vs). While BEVs are generally more efficient, the study highlights the limitations posed by seasonal energy storage. In contrast, H2-FCEVs and SNG-Vs can store surplus energy for later use, though they face efficiency losses during conversion. These findings underscore the need for technological innovations in energy storage to optimize the long-term sustainability of electric mobility (Rüdisüli et al., 2022).

Closed-loop supply chains (CLSCs) for EV batteries offer another potential avenue for enhancing sustainability by encouraging the recycling and reuse of batteries. Gu et al. (2018) have developed models to optimize the profitability of battery reuse and recycling, finding that while battery reuse can significantly reduce raw material consumption, the profitability of recycling operations is often constrained by high processing costs. The study emphasizes the importance of developing simplified models accessible to practitioners and suggests that government incentives or technological advancements may be critical in making battery recycling more financially viable.

The global disruptions caused by the COVID-19 pandemic have also profoundly affected the EV industry, as highlighted by Wen et al. (2021). Their analysis of the Chinese EV market reveals how supply chains for critical components, such as lithium and cobalt, were severely disrupted. The study indicates that while government incentives helped stimulate a market recovery in the second half of 2020, long-term vulnerabilities remain. This raises questions about the resilience of global EV supply chains, particularly in regions outside of China, and points to the need for further research into how these disruptions will shape the industry's future.

This paper provides a comprehensive review of electric vehicle (EV) supply chain management, focusing on the challenges and opportunities the growing demand for EVs presents. It explores critical areas such as the thermal management systems (TMS) of lithium-ion batteries (LIBs), the environmental implications of various mobility technologies, and the development of closed-loop supply chains (CLSCs) for EV batteries. Additionally, it analyzes the impacts of the COVID-19 pandemic on global EV supply chains, highlighting the disruptions and vulnerabilities exposed by the crisis. The paper identifies significant research gaps in areas like real-world validation, alternative battery chemistries, and supply chain governance, and calls for further investigation into these domains to ensure the sustainability and scalability of the EV industry.

## II. LITERATURE REVIEW

The literature on electric vehicle (EV) supply chain management has been rapidly evolving as researchers seek to address the challenges and opportunities of the growing demand for electric mobility. One of the key research areas is the thermal management system (TMS) for lithium-ion batteries (LIBs), which are essential for maintaining battery performance, safety, and longevity in EVs. The paper by Murugan et al. (2022) offers a comprehensive bibliometric analysis of global research trends on TMS from 2000 to 2021, utilizing the Scopus database. The study identifies China as the dominant contributor to research in this field, followed by the United States and Germany. Air cooling and phase change materials (PCMs) are among the most commonly explored techniques for managing battery temperatures, though much of the research is still focused on numerical modeling rather than experimental validation. The authors highlight a gap in exploring other battery chemistries and stress the need for more global collaboration in the field of LIB thermal management (Murugan et al., 2022).

Similarly, Rüdisüli et al. (2022) explore the environmental implications of electricity-based mobility options, such as battery electric vehicles (BEVs), hydrogen fuel cell electric vehicles (H2-FCEVs), and synthetic natural gas vehicles (SNG-Vs). Through a life-cycle assessment (LCA) approach, the authors analyze the greenhouse gas (GHG) emissions of these technologies, emphasizing the importance of low-carbon electricity in achieving significant emissions reductions. However, the study notes limitations in seasonal energy storage for BEVs and calls for further technological advancements in H2-FCEVs and SNG-Vs to reduce energy losses during conversion processes. The research is centered on the Swiss and European contexts, raising questions about the transferability of findings to other regions with different energy systems (Rüdisüli et al., 2022).

Another study by Gu et al. (2018) addresses the economic and environmental aspects of electric vehicle battery closed-loop supply chains (CLSCs). By modeling a three-period lifecycle of EV batteries, the authors explore profit-maximizing strategies for manufacturers and remanufacturers. While the study demonstrates that battery reuse can increase profits and reduce raw material consumption, it also reveals the limited profitability of recycling operations due to high costs. The authors call for more simplified models to make the economic viability of recycling more accessible to practitioners and propose further research on government incentives and advancements in recycling technology (Gu et al., 2018).

The impact of global disruptions, such as the COVID-19 pandemic, on the EV industry is another critical area of research. Wen et al. (2021) analyze the pandemic's effects on the Chinese EV market, revealing significant disruptions in both supply chains and consumer demand. The study shows that government incentives helped revive the market in the latter half of 2020, but it also underscores the pandemic's exposure of vulnerabilities in global supply chains, particularly for critical components like lithium, cobalt, and nickel. The authors suggest that further research is needed to assess the long-term impact of the pandemic on global EV supply chains and consumer preferences (Wen et al., 2021).

Moreover, Jing et al. (2021) focus on the reuse of retired EV batteries in distributed energy systems (DES), proposing a profit-allocation framework to optimize the integration of these batteries into energy storage applications. While the study highlights the environmental and economic benefits of battery reuse, it identifies gaps in understanding the technical constraints and market volume for retired batteries. The authors recommend further exploration of policies and incentives to support the profitability of battery reuse and recycling (Jing et al., 2021).

Kalaitzi et al. (2019) examine resource dependencies in EV supply chains during production ramp-up, focusing on how these dependencies impact scaling for niche manufacturers. The authors identify buffering and bridging strategies suppliers use to mitigate risks associated with resource dependency but note that existing research has primarily focused on dyadic relationships rather than multi-tier supply chains. The study calls for more research on how small and medium-sized enterprises (SMEs) can manage resource dependencies effectively in a rapidly evolving industry dominated by large players (Kalaitzi et al., 2019).

Lastly, Agusdinata et al. (2022) discuss the socio-environmental challenges of extracting critical minerals for EV production, such as cobalt, lithium, and rare earth elements. Using a telecoupling framework, the study examines the global interdependencies in the supply chain and highlights the fragmented nature of governance structures, with little coordination between regions involved in mineral extraction and consumption. The authors suggest that more robust governance mechanisms are needed to mitigate the negative externalities of mining activities and ensure the sustainability of the EV supply chain (Agusdinata et al., 2022).

Collectively, these studies highlight the diverse and complex challenges facing the EV supply chain, from thermal management and lifecycle emissions to resource dependencies and global disruptions. They underscore the need for more comprehensive and collaborative approaches to research, particularly in areas like sustainability, recycling, and supply chain resilience. The research gaps identified in these studies provide valuable direction for future work, emphasizing the importance of developing innovative solutions that address economic and environmental considerations in the rapidly expanding EV industry.

## III. RESEARCH GAPS

The research on electric vehicle (EV) supply chains has highlighted several underexplored areas, especially regarding technical, environmental, and strategic management challenges. A key gap identified is in EVs' thermal management systems (TMS) for lithium-ion batteries (LIBs). Murugan et al. (2022) pointed out that most research in this area is focused on numerical modeling, leaving a significant gap in real-world experimental validation. Despite the attention given to LIBs, there remains limited exploration of alternative battery chemistries, such as solid-state and sodium-ion batteries, which could offer improved thermal performance. This suggests that future research needs to move beyond theory and into practical applications to improve battery performance and safety.

Life-cycle assessment (LCA) and energy storage also reveal critical gaps in the environmental evaluation of mobility options. Rüdisüli et al. (2022) note that while battery electric vehicles (BEVs) tend to have lower greenhouse gas (GHG) emissions, limitations in seasonal energy storage hinder their effectiveness. Additionally, hydrogen fuel cell electric vehicles (H2-FCEVs) and synthetic natural gas vehicles (SNG-Vs) suffer from energy losses during conversion processes, requiring technological advancements to enhance their efficiency. This underscores the need for further research to optimize energy storage solutions, particularly in regions beyond Europe and Switzerland, where energy systems may differ significantly.

In terms of supply chain sustainability, Gu et al. (2018) identify challenges in implementing closed-loop supply chains (CLSCs) for EV batteries, emphasizing that while battery reuse can contribute to sustainability, the economic viability of recycling operations is often limited by high costs. Many existing models are overly complex for practical application, suggesting that simplified, yet effective, models are needed to optimize battery reuse and recycling. The study also highlights the potential role of government incentives and technological advancements in making battery recycling more financially viable, an area that remains underexplored in the literature.

The impact of global disruptions, such as the COVID-19 pandemic, on the EV industry has also exposed significant research gaps. Wen et al. (2021) demonstrate the profound short-term disruptions to EV supply chains, particularly in China, due to the pandemic. However, the long-term effects on global EV production remain insufficiently studied. There is a particular need for research into how these disruptions will affect supply chain vulnerabilities in regions outside China, such as Europe and the United States, as well as the potential strategies for mitigating future disruptions.

Another underexplored area is reusing retired EV batteries within distributed energy systems (DES). Jing et al. (2021) identify gaps in understanding the technical constraints and market volume for retired batteries and the lack of comprehensive studies that examine the entire supply chain from a circular economy perspective. More detailed research is needed to assess the role of policy incentives in supporting battery reuse and recycling, as these could significantly enhance the profitability and environmental sustainability of the DES sector.

Resource dependencies within EV supply chains, especially during production ramp-up, present further challenges. Kalaitzi et al. (2019) highlight that current research largely focuses on dyadic relationships between buyers and suppliers, neglecting the complexities of multi-tier supply chains. This gap is particularly problematic for small and medium-sized enterprises (SMEs) that face difficulties scaling production while managing resource dependencies. Future research should explore strategies to help SMEs navigate these dependencies effectively, particularly in a resource-constrained environment dominated by larger players.

Finally, sustainability and governance of critical mineral supply chains are also significant areas of concern. Agusdinata et al. (2022) emphasize the fragmented governance frameworks that exist in the extraction and consumption of critical minerals such as cobalt and lithium. The lack of comprehensive governance mechanisms, coupled with limited consumer awareness and corporate social responsibility (CSR) initiatives, suggests that future research should focus on developing robust governance structures that address the socio-environmental impacts of mining activities and ensure the long-term sustainability of the EV supply chain.

In summary, while significant progress has been made in advancing EV supply chains, there are still several key areas that require further investigation, particularly in real-world validation, economic viability, and sustainable practices. Addressing these research gaps will be critical in ensuring the long-term success and scalability of the EV industry, especially as it continues to grow in response to global sustainability goals.

## IV. METHODOLGY

To address the research gaps identified in the literature on electric vehicle (EV) supply chain management, a comprehensive research methodology is proposed that targets key areas such as experimental validation, circular economy models, and the governance of critical mineral supply chains. This methodology is structured to provide actionable solutions that bridge the gaps in existing research and contribute to the scalability and sustainability of EV production.

### *A. Experimental Validation of Thermal Management Systems (TMS) for Lithium-Ion Batteries (LIBs)*

A mixed-method approach can be adopted to address the lack of real-world experimental validation of thermal management systems (Murugan et al., 2022). This includes the design of controlled laboratory experiments to evaluate the performance of air cooling, liquid cooling, and phase change materials (PCMs) under various operational conditions, such as different ambient temperatures, charge/discharge cycles, and driving patterns. The experimental phase will involve collecting thermal data from LIBs during dynamic testing in EV prototypes, using advanced thermal imaging and sensor networks to track heat dissipation and hotspots in real-time. The experimental data can then be compared to existing numerical models to validate or refine them for practical applicability. Additionally, alternative battery chemistries, such as solid-state and sodium-ion batteries, should be experimentally tested for their thermal performance, to evaluate their potential as alternatives to LIBs.

### *B. Optimization of Seasonal Energy Storage for BEVs*

A simulation-based research approach can be employed to mitigate the limitations in seasonal energy storage for battery electric vehicles (BEVs) identified by Rüdisüli et al. (2022). This involves the development of simulation models to evaluate the long-term storage capabilities of BEV batteries under varying levels of renewable energy supply, particularly solar and wind power. The models should incorporate energy flow optimization techniques that balance short-term and long-term storage needs. Furthermore, integration with renewable energy grids can be modeled to assess how BEVs, hydrogen fuel cell electric vehicles (H2-FCEVs), and synthetic natural gas vehicles (SNG-Vs) interact with energy storage systems. The simulation will also include sensitivity analyses to account for varying grid capacities, seasonal fluctuations in energy generation, and battery degradation rates. Real-world pilot studies can complement these simulations by testing the viability of advanced energy storage systems and optimizing them for real-world application.

*C. 3. Simplified Closed-Loop Supply Chain (CLSC) Models for EV Batteries*

In response to the need for simplified, practical models for closed-loop supply chains (CLSCs) of EV batteries (Gu et al., 2018), the proposed methodology focuses on developing user-friendly decision support systems (DSS). This will involve creating mathematical models that streamline the optimization of battery recycling and reuse processes, while incorporating economic variables like return yields, sorting rates, remanufacturing costs, and government incentives. These models will be developed using operations research techniques such as linear programming and game theory to optimize profit distribution among manufacturers, recyclers, and remanufacturers. The models will be validated through case studies and pilot projects with industry partners, focusing on scalability, ease of use, and practical applicability for supply chain managers. Additionally, a policy analysis framework can be integrated into the models to evaluate the impact of potential government incentives on the profitability and sustainability of battery recycling initiatives.

*D. Longitudinal Study on Global EV Supply Chain Resilience Post-COVID*

A longitudinal study will be conducted to address the research gap in understanding the long-term impacts of the COVID-19 pandemic on global EV supply chains (Wen et al., 2021). This study will track supply chain performance indicators across different regions, such as production volumes, lead times, and supplier disruptions over multiple years. Data will be collected from industry sources, government reports, and company disclosures, focusing on identifying persistent vulnerabilities in critical component supply chains, particularly for materials like lithium, cobalt, and nickel. The longitudinal analysis will also explore how firms adapt their strategies over time, such as diversifying their supplier base, reshoring production, or investing in digital supply chain technologies. In addition to quantitative analysis, qualitative interviews with key industry stakeholders will provide insights into how firms and policymakers address these long-term supply chain challenges.

*E. Circular Economy for Retired EV Batteries in Distributed Energy Systems (DES)*

To explore the potential of retired EV batteries in distributed energy systems (DES), as suggested by Jing et al. (2021), a comprehensive techno-economic assessment methodology will be developed. This approach will involve modeling the entire lifecycle of retired batteries from EVs to their second use in DES applications, focusing on optimizing battery reconfiguration, storage, and deployment strategies. The economic viability of these applications will be evaluated through cost-benefit analyses, considering the cost of repurposing batteries, transportation, installation, and maintenance. Additionally, a policy impact assessment will be conducted to determine the effect of government incentives on DES adoption, such as feed-in tariffs, tax credits, or subsidies for energy storage. Pilot projects will be implemented in urban areas to test the real-world performance of retired batteries in DES and to identify any technical challenges that may arise during their integration.

*F. Multi-Tier Resource Dependency Mitigation Strategies*

To address the gaps in managing resource dependencies in multi-tier EV supply chains (Kalaitzi et al., 2019), a multi-tier network analysis framework will be developed. This methodology will use network modeling to map out the dependencies across different tiers of the supply chain, focusing on the flow of critical resources like batteries, fuel cells, and electronic components. The framework will identify potential bottlenecks and vulnerabilities in the supply chain and evaluate mitigation strategies such as diversifying suppliers, increasing inventory buffers, and developing strategic partnerships. A multi-criteria decision analysis (MCDA) tool will be incorporated to assist SMEs in selecting the most effective strategies for managing their resource dependencies, based on criteria such as cost, lead time, and supply chain resilience. The framework will be validated through case studies of niche EV manufacturers to ensure its applicability in real-world scenarios.

### *G. Telecoupling Framework for Governance of Critical Mineral Supply Chains*

To address the fragmented governance structures and lack of comprehensive frameworks for managing the critical mineral supply chain (Agusdinata et al., 2022), a telecoupling framework will be developed. This framework will focus on integrating the perspectives of sending (extraction) and receiving (consumption) regions, while promoting sustainability across the global supply chain. The framework will involve multi-stakeholder engagement, including governments, corporations, and local communities, to develop coordinated policies that address the socio-environmental impacts of mineral extraction. Scenario planning and policy simulations will be used to explore different governance structures, and their effectiveness will be evaluated through comparative case studies of critical mineral supply chains in different regions. This approach will help to identify best practices for achieving sustainable and equitable outcomes in the global EV supply chain.

## V. CONCLUSIONS

The results from the literature highlight that the thermal management systems (TMS) for lithium-ion batteries (LIBs) in electric vehicles (EVs) remain heavily reliant on numerical modeling, with insufficient experimental validation. Murugan et al. (2022) demonstrate that while techniques such as air cooling and phase change materials (PCMs) are popular in theory, their practical application is yet to be fully explored. The study indicates that China, the United States, and Germany are key contributors to this field, although collaborative efforts across different nations are limited. This lack of global research partnerships is seen as a hindrance to advancing the thermal performance of LIBs. The research concludes that experimental studies on alternative battery chemistries, such as solid-state and sodium-ion batteries, could significantly enhance the understanding of thermal management, paving the way for more effective and safe EV battery systems.

Regarding environmental implications, Rüdisüli et al. (2022) highlight the benefits and limitations of different electricity-based mobility options. The study confirms that battery electric vehicles (BEVs) exhibit the lowest greenhouse gas (GHG) emissions when coupled with low-carbon electricity. However, in cases where renewable energy is curtailed, hydrogen fuel cell electric vehicles (H2-FCEVs) and synthetic natural gas vehicles (SNG-Vs) outperform BEVs due to their ability to store excess electricity. Despite this, significant energy losses during conversion processes indicate a need for further advancements in these technologies. The findings emphasize the importance of optimizing seasonal energy storage and energy system flexibility to fully realize the environmental benefits of these alternative technologies. The study concludes that while Europe and Switzerland have made progress in this area, more research is required to adapt these findings to different regional contexts.

Closed-loop supply chains (CLSCs) for EV batteries present a promising opportunity for both economic and environmental sustainability, as explored by Gu et al. (2018). Their study reveals that while battery reuse can reduce raw material consumption and enhance profits, recycling operations remain economically challenging due to high processing costs. The results suggest that government incentives and technological advancements in recycling are necessary to make these practices more viable. Furthermore, the study points out the need for simplified models that can be more easily applied by practitioners in real-world settings, thereby improving the practicality of closed-loop systems in the EV industry. In conclusion, Gu et al. (2018) advocate for greater policy support and innovation to enhance the profitability and feasibility of recycling within EV battery supply chains.

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