The shaping of EV battery supply chains: Resilience challenges and circular economy alternatives

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Abstract

Purpose
The growing demand for EV (electric vehicle) batteries is driving the emergence of global supply chains highly dependent on the extraction of critical mineral metals. Such dependence brings new challenges to the sustainability and resilience of EV battery supply chains in the automotive sector. This paper sheds light on the resource dependence constraints and sustainability challenges shaping the configuration of emerging EV battery supply chains.

Research Approach
A horizon-scanning approach is taken to capture insights from current studies and industrial trends in the automotive sector. The paper draws from Resource Dependence Theory (RDT) important concepts to characterise buffering and bridging strategies to address resource dependence issues concerning the sourcing of critical minerals. The identified strategies are linked to circular economy solutions for end-of-life recovery of EV battery metals.

Findings and Originality
The paper points out critical resource dependencies posing resilience and sustainability challenges to EV battery supply chains. The conceptual connections between RDT and circular economy offer an original theoretical perspective, supporting the elaboration of purposeful circular economy approaches to address key resilience and sustainability challenges in EV battery supply chains. To address emerging challenges, the creation of circular supply chains, where essential metals can be 'mined back' from end-of-life batteries, has become of strategic importance.

Research Impact
The paper contributes to developing a better understanding of the contextual and operational complexities involved in the management of emerging EV battery supply chains. It also offers an original theoretical perspective linking RDT with circular economy approaches, this way expanding knowledge in the area.

Practical Impact
The paper shows that the recovery of secondary raw materials through battery recycling will be of crucial importance to address resource dependence issues concerning the automotive sector. The linkages between RDT buffering/bridging strategies and specific circular economy approaches provide a helpful managerial framework to support supply chain managers to strategically address resource dependence challenges faced by EV battery supply chains.

Keywords:
EV Battery Supply Chains, Supply Chain Resilience, Resource Dependence Theory, Circular Economy.

Introduction – research background

The automotive industry is currently going through an unprecedented transformation in the vehicles' energy systems due to a global shift from the production of vehicles powered by internal combustion engines to the production of electric vehicles (EV) where the engines' main energy source is electric batteries. The increase of EV production by major car manufacturers is driving a growing demand for EV batteries, which is consequently causing an upsurge on the mining of non-renewable raw materials (e.g. mineral metals) necessary to produce the batteries (Jones *et al*., 2020). Such trend raises serious concerns about the resilience and sustainability of EV battery supply chains.

For instance, a recent report by the European Commission (EC, 2022) identifies a critical dependency on essential minerals for battery manufacturing such as lithium, cobalt, nickel, graphite, manganese, etc. Global vehicle and large-scale battery manufacturers (gigafactories) are increasing competition to secure the sourcing of essential EV battery raw materials, with the demand for lithium, cobalt, nickel and graphite expected to increase substantially over the next years due to their application in other energy technologies such as fuel cells, wind turbines and photovoltaics. The reserves of essential minerals are limited to a few geographical regions worldwide, quite often located in countries with volatile political and economic scenarios.

Problems also arise downstream supply chains, as batteries disposal is costly and damaging to the environment. Thus, the creation of circular supply chains where essential metals can be 'mined back' from end-of-life battery cycles has become of crucial importance to minimise primary extraction and disposal flows. While the recycling capacity of EV batteries is increasing, circular economy approaches based on prolonging the utility of batteries and components are still underexploited.

So far, there is little research considering how firms can effectively manage the uncertainties concerning the resilience and sustainability of emerging EV battery supply chains. This is a complex issue where, on one hand, supply chain resilience entails the strategic management of critical resource dependencies concerning the sourcing of primary raw materials and, on the other hand, supply chain sustainability entails the sourcing of secondary raw materials recovered from used batteries. The literature in this field is growing on a fragmented basis, addressing the problems above mentioned from different theoretical lenses and practical angles. This is typical of emerging research addressing new fields of managerial knowledge, where diverse management perspectives are developed to address pressing problems.

However, considering the substantial scale of industrial transitions towards the deployment of electric vehicles in the global market, the development of integrative research is necessary to support a more coherent and comprehensive understanding of how automotive firms are dealing with resilience and sustainability challenges in their EV battery supply chains, and the holistic managerial approaches to address related challenges. To this end, the paper draws from **Resource Dependence Theory (RDT)** important concepts to characterise firms' strategies to address supply chain management issues concerning the sourcing of critical EV battery raw materials. The identified strategies are linked to potential **circular economy approaches** to recovering end-of-life EV battery materials.

From the context above mentioned, we derive the following **research questions** to be addressed in this paper:

1. How automotive firms are responding to critical resource dependence and sustainability challenges faced by their EV battery supply chains?
2. How circular economy approaches can support the implementation of resource dependence minimisation strategies in EV battery supply chains?

Theoretical basis

EV battery supply chains – critical resources and challenges

EV battery technologies are growing fast, motivated by the increasing market demand and commercial opportunities. Currently, the majority of EV battery technologies are still fundamentally based on lithium-ion chemistries that involve the processing of critical minerals such as lithium, nickel, cobalt, manganese, graphite, and so forth. These essential minerals form the basis of battery cells, which are core battery elements packed together to produce the final EV battery units in different forms and shapes. However, the entire EV battery manufacturing process is by no means a simple process. It involves a number of processing and manufacturing steps, from mining and refinery activities upstream the supply chain to end-of-life activities downstream, as illustrated in Figure 1.

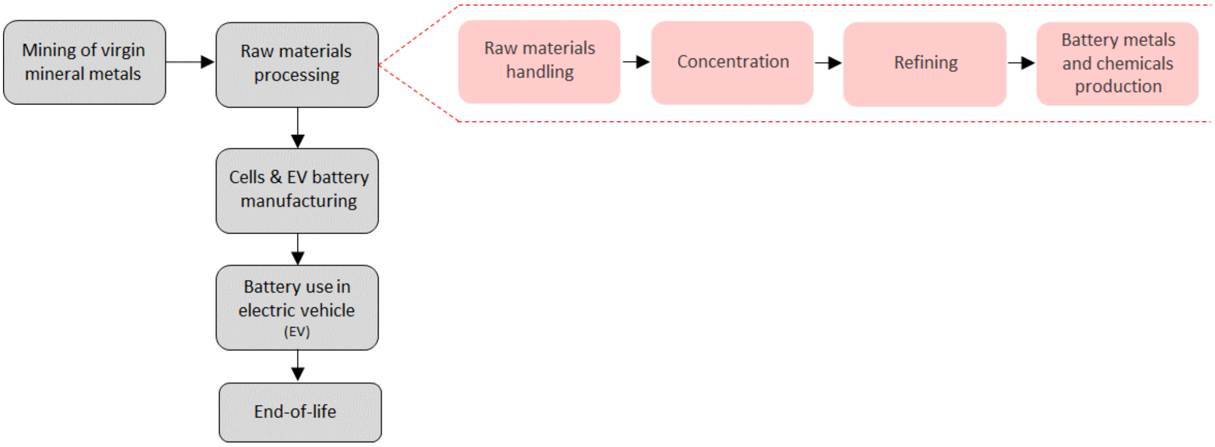

Figure 1 – Linear supply chain perspective of an EV battery lifecycle

Global EV battery supply chains face critical resilience challenges to sustain battery production. Some of the major challenges identified by recent studies in the area (Cheng *et al*., 2024; Barman *et al*., 2023) refer to issues concerning the continuity and stability of raw materials sourcing, specifically:

- There is a critical dependence on the mining capacity of essential minerals to meet the scale of expected demands for EV batteries in the automotive industry. A recent study by Jones *et al*. (2020) has projected a global increase for the demand of EVs of approximately 13% by 2030, which will reflect as large increases in the demand for base metals, including a 37-fold (from 5 to 185 thousand tonnes) and 18-fold (from 8 to 147 thousand tonnes) increase in the demand for cobalt and lithium respectively, compared to 2015 levels.
- The is also a critical dependence on essential minerals whose mine reserves are mainly concentrated in geographical locations and countries with volatile economy and political contexts.
- There is a critical dependency on China as a major global supplier of lithium-ion batteries and cells. The Chinese company CATL (Contemporary Amperex Technology Limited) is the largest global battery group. China is also dominant in the supply of graphite, concentrating approximately 80% of the global supply.
- Russia is one of the main global suppliers of battery-grade nickel. The Russia–Ukraine conflict has significantly affected the supply of nickel globally.

The external factors above mentioned are related to serious resource dependence issues, which pose considerable threats to the resilience of global EV battery supply chains. Automotive firms are responding to resilience challenges in different ways, competing for suppliers and developing their own battery manufacturing capacity (Bridge & Faigen, 2022; Kalaitzi *et al*., 2019). The variety of industrial responses creates a dispersed picture of managerial initiatives being developed by firms in the sector, which makes it difficult to explain emerging patterns in the management of EV battery supply chains and to conduct comparative analysis of managerial practices across diverse automotive firms.

As we are ultimately investigating a resource dependence problem in the automotive industry, we logically selected the Resource Dependence Theory as the theoretical lens from which we draw core principles, concepts, and managerial frameworks that can be used as a common ground to support strategic supply chain responses to address resilience challenges in EV battery supply chains.

Resource dependence theory

Resource Dependence Theory (RDT) is a useful theoretical perspective to help managers to address resilience challenges in EV battery supply chains. A fundamental RDT premise is the recognition that organisations are influenced by external factors. From this, it follows that managers should act to minimise uncertainties and dependence on external factors that negatively impact or posit risks to their organisations (Hillman *et al*., 2009).

From the many aspects within the theoretical scope of RDT, the concepts of **buffering** and **bridging** strategies are particularly considered in this study, as they provide specific managerial frameworks for firms to reduce resource dependence. For example, buffering capabilities can be built, inter alia, through the following initiatives (Manhart *et al*., 2020): **a.** development of manufacturing capacity to adapt to supply chain disruptions; **b.** specification of precautional safety stock levels and substitute resources; **c.** agreements with backup suppliers.

On the other hand, bridging strategies involve managing the relationships with key stakeholders in the supply chain in order to secure the resources required for continuous operations. Examples of bridging strategies (Schnittfeld & Busch, 2016) include **a.** development of close relationships with suppliers through cooperation initiatives and long-term commitments; **b.** prioritization of initiatives to allocate limited resources; **c.** ongoing monitoring of supply chain changes or trends; **d.** information sharing with key suppliers; **e.** joint planning to improve forecasting and replenishment capabilities.

Previous studies have found that when production volumes increase, bridging strategies become essential to build supply chain collaborations and close relationships with key suppliers (Kalaitzi *et al*., 2019). Such bridging initiatives lead suppliers to not only provide critical resources more regularly, but also take the role of supply chain orchestrators, offering direct support to EV manufacturers. Overall, supply transparency and information sharing are critical for the successful implementation of buffering and bridging strategies (Manhart *et al*., 2020; Schnittfeld & Busch, 2016).

Circular economy – main resource recovery approaches

Securing the sourcing of essential mineral metals upstream the supply chain is not a sufficient solution to the resilience challenges faced by the automotive industry. Recovering secondary raw materials downstream, i.e. metals extracted from end-of-life EV batteries, is crucially important as well for two reasons. First, increasing the supply of essential metals from battery recycling sources is considered as an important contributor to the future of EV battery supply chains (Heijlen *et al*., 2021; Fu *et al*., 2020). Second, the automotive industry has to deal with the environmental impact of EV battery waste. Despite having lower environmental impact than traditional batteries used in internal combustion engines, EV batteries have the presence of toxic materials which present risks to human health and the environment (Amusa *et al*., 2024).

From the reasons above, we conclude that the development of sustainable alternatives for end-of-life EV batteries is of strategic importance to address potential risks of resources shortages and mitigate environmental and social risks. We therefore argue that the implementation of resilient and sustainable EV battery supply chains requires a circular supply chain management approach to enable the circularity (closed loops) of essential battery metals.

The circular economy places central importance on the closed-loop flows of materials, as they enable the circularity capability expected from sustainability-oriented supply chains, which creates value for secondary raw materials while minimising the consumption of primary raw materials (Batista *et al*., 2023). In practice, circular supply chains support the implementation of key restorative (circular) approaches advocated by the circular economy, which are generically referred to as the 'R' approaches involving reuse, repair, refurbish, remanufacture, recycling, etc., and other resource recovery activities that help reducing the dependence on primary resources (Batista *et al*., 2018).

Currently, the predominant approach to recover secondary raw materials from used EV batteries is **recycling**, which places battery recyclers as key new entrants in the circular supply chains being implemented by automotive companies. Other circular economy approaches such as battery **upcycling** alternatives based on battery repurposing are somewhat overlooked in the sector. In this study, we link alternative circular economy approaches to battery recycling/upcycling with RDT buffering/bridging strategies and make some conclusions about their potential role in improving the resilience and sustainability of EV battery supply chains. The theoretical framework for the study is shown in Figure 2.

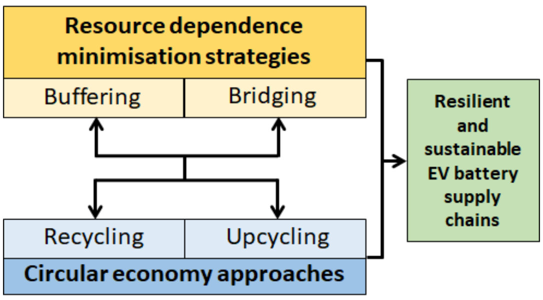

Figure 2 – Theoretical framework

Methodology

The study adopted a horizon-scanning approach to characterising supply chain scenarios in the automotive sector aimed at improving the resilience and sustainability of EV battery supply chains. The resilience and sustainability approaches considered were linked with resource dependence theory and circular economy strategies.

Horizon scanning is a research method aimed at detecting early signs of important developments through the examination of potential threats and opportunities, with emphasis on organisational approaches and their possible effects on the subject of interest. We applied this method to explore new and unexpected issues as well as persistent problems and trends, including issues at the margin of current thinking that may posit challenges to current assumptions.

The horizon scanning process involved focused desk research aimed at developing a comprehensive understanding of the wider sectoral context where EV battery supply chains are being implemented. In this process, we consulted a wide variety of academic literature as well as the grey literature comprising industry publications, white papers and relevant internet-based articles from relevant sources and reputable institutions.

The method supported the initial stage of a wider exploratory research being developed to characterise and structure the research subject, giving the topic a more coherent theoretical and practical basis. Overall, the methodology allowed the generation of valuable insights on the sector analysed, shedding light on the main upstream (sourcing) and downstream (use and recovery) supply chain challenges the electrification of the automotive sector is facing.

Research findings and discussion

The electrification of vehicles is an important industrial transition for reducing carbon emission levels in the automotive sector. However, as the sector eliminates dependence on fossil fuels, the upsurge on demand for EV batteries brings new environmental and resource dependence concerns. Despite this fundamental transition in the sector, the energy systems powering EVs remain dependent on the extraction of non-renewable mineral resources.

Minimising the dependence on primary raw materials is therefore of critical importance. To this end, major battery and car manufacturers are implementing a number of buffering and bridging strategies to secure the sourcing of primary raw materials and create supply of secondary raw materials produced. For example, Tesla, a first mover in the production of electric vehicles, is developing its buffering capabilities by building its own lithium refinery in the US, which is expected to become fully operational in 2025 (tesla.com). The company is also developing bridging strategies by working with multiple suppliers of battery cells containing nickel and cobalt.

Securing the supply of secondary raw materials for EV battery production is also of strategic importance for automotive firms. Besides improving the environmental sustainability of the supply chains in the sector, recovering resources from used batteries reduces the dependence on primary raw materials. In this context, circular economy approaches become crucially important, as they provide a wide range of closed-loop alternatives that can support buffering and bridging strategies to improve the sourcing of secondary raw materials. For instance, the South Korean company LG Energy Solution (LGES), one of the world's largest battery manufacturers, is developing buffering capabilities for the supply of secondary raw materials by developing technologies to maximise battery recycling and implementing circular supply chains to collect and recycle non-reusable batteries (Sandridge, 2023). In terms of bridging strategies, LGES is seeking to ensure a stable supply of secondary raw materials by collecting end-of-life batteries from global manufacturing sites via strategic cooperations with major recycling companies. This initiative also involves battery refurbishing, reconditioning, and upcycling applications (e.g. manufacturing of smaller batteries for electric scouters, bikes, energy stations, etc.).

In practice, at the end-of-life phase of an EV battery, various circularity strategies can be utilised, such as reuse, remanufacturing, repurposing, and recycling. While the second use of batteries may not always be the best option due to different application requirements, the remanufacturing of EV batteries is seen as a promising circular economy alternative for the sector in the future (Alamerew & Brissaud, 2020).

EV battery components, including cells and peripheral modules, are well-suited for the remanufacturing process. The economic feasibility of remanufactured EV battery components is dependent on the future price of spare parts. Studies have shown that remanufacturing batteries can be economically beneficial, with cost-benefit analyses indicating potential savings of up to 40% compared to using new batteries (Alamerew & Brissaud, 2020).

In terms of recycling, the number of circular supply chains being implemented by automotive OEMs are growing. But the initiatives are still limited given the size of the industry. Some European examples are the strategic research collaboration between Umicore and Audi, which aims to recover 90% of cobalt and nickel from Lithium-ion battery modules. Other companies such as BMW and Volkswagen are also implementing a closed-loop recycling process (Albertsen *et al.*, 2021).

The lack of a streamlined and affordable collection system in various regions is a barrier to the widespread adoption of recycling and upcycling approaches, particularly for cobalt batteries with lower recycling returns (Rajaeifar *et al.*, 2022). Additionally, challenges such as high transportation costs and the need for battery shipment standards and regulations worldwide must also be tackled in order to facilitate commercialisation efforts.

Conclusion

This paper develops an initial horizon scanning analysis of current trends in the supply chains of EV batteries. Drawing from RDT and circular economy perspectives, we provide brief insights on how automotive firms are responding to critical resource dependence and sustainability challenges faced by their EV battery supply chains. We also point out some circular economy approaches supporting the implementation of resource dependence minimisation strategies such as buffering and bridging.

The substantial changes in the landscape of automotive supply chains are complex, which calls for further research in the area. For instance, EV battery technologies are rapidly improving, generating considerable investments into EV programs and bringing a number of new supply chain players from a variety of industries. In this context, geopolitical tensions and battery charging infrastructure challenges need in-depth investigations. The implications of the growing mining of essential minerals raises concerns on the social sustainability of EV battery supply chains. This aspect deserves further investigation. For instance, the mining industry presents several cases of labour exploitation (Hofmann *et al*., 2018). Such cases can be linked to the supply chains of companies supplying goods we consume. In 2019 large corporations such as Tesla, Apple, Alphabet (Google's parent company), Microsoft and Dell have been accused of being complicit in the death of children in Congo forced to mine cobalt (Lavietes, 2019). The alleged companies argued they would never 'knowingly' source materials from suppliers using child labour. This reveals the alarming inability of major global importers to detect and address labour exploitation practices in their supply chains. Investing how the visibility and transparency of EV battery supply chains can be improved is also a key area for future research.

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