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Investigating context-specific factors for the development of circular business models for end-of-life electric vehicle lithium batteries in Australia

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A R T I C L E I N F O

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A B S T R A C T

Considering the rapid adoption of lithium batteries in electric vehicles (EV), several tonnes of lithium batteries are expected to reach end-of-life in the coming years. These batteries, if disposed in landfill, presents concerns to the environment and human health. Moreover, end-of-life EV lithium batteries still retain a certain extent of their initial capacity. Hence, a circular economy (CE) approach has been proposed as a possible solution to overcome these challenges. Effective circular business models play a vital role for the adoption of circular practices throughout the industry considering the development of such models are context specific. Therefore, this research aims to explore and investigate context-specific factors required to develop a circular business model for end-of-life EV lithium batteries in Australia.

This study applies an inductive approach drawing from themes arising from semi-structured interviews of five stakeholder groups related to the EV lithium battery industry. The level of influence of government policies, knowledge and understanding of CE, and the dependence on EU and other nations were found to influence the EV battery industry. Particularly, the findings suggest the knowledge of 'how to be involved in CE initiatives' was lacking and should be given importance. Therefore, the importance of collaboration not only between government and industry but also involving academics and research institutions is highlighted. Based on these contextual factors, implementing the 10R strategy relative to the prevalent 3R or 4R strategy for the development and classification of circular business models for end-of-life EV lithium batteries in Australia is suggested. Academic contributions and managerial implications followed by recommendations to policy makers are provided.

1. Introduction

Lithium-ion batteries (LiBs) are increasing in popularity due to their applications in portable electronics and recently the emerging electric vehicle (EV) market (Ahuja et al., 2020). Canals et al. (2022) stated that the steady momentum of the EV uptake is undeniable. EV sales in 2020 accounted for 4% of global vehicle sales, while it has steadily increased to nearly 18% of global vehicle sales in 2023 (International energy agency, 2023). In Australia alone, the number of EVs exceeded to more than 180,000 as of 2023 (Thompson, 2024). EVs are generally powered by a lithium-ion battery (LiB) pack which contain a typical life span of 5–15 years (Vu et al. 2020), with several million EV LiBs expected to reach end-of-life (EOL) in the next five to ten years (Chirumalla et al., 2022). In Australia, it is forecast that the volume of EOL LiBs will be between 137,000 and 180,000 tonnes in 2036 (King and Boxall, 2019) influenced by the recent EV adoption rates (Zhao et al., 2021a). This highlights the need to develop a solution to avoid the disposal of EOL EV LiBs to landfill and effectively mitigate adverse effects to the environment and its resultant implication to human health.

EV LiBs after their application in EVs generally retain up to 70–80% of their operating capacity (Olsson et al., 2018) at EOL. Therefore, circular economy (CE) principles could be used to harness the residual value in the materials in the most sustainable manner (Ahuja et al., 2020; Sopha et al., 2022), while relying on circular business models (CBMs) which are essential to transition into CE (Albertsen et al., 2021). The key difference between CE and CBM is that CE is an economic model focusing on the preservation, improvement and utilisation of products and materials for as long as possible through the R strategies (Table 1), while CBM is an initiative that enables organisations to create value by following the CE principles (Hina et al., 2022).

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Table 1
Interpretations of 10 R strategies as applied to EV LiBs (Source: Authors).

R strategy	Description/Explanation	Reference
Refuse	Refuse refers to the prevention of the use of raw materials for the production of EV batteries	
Reduce	This R strategy refers to the reduction in the reliance of raw materials necessary to implement a CE strategy for EV batteries	Baars et al. (2021)
Renew	Renew refers to redesigning a product to incorporate the design principles of CE. The concept of redesign in the context of CBMs was termed as a requirement for extending the life of an EV battery	Alamerew & Brissaud (2020)
Re-use	EV LiB at EOL can be used for the same application i.e., EVs, provided the battery system indicated a high state of health involving minimal modifications.	Börner et al. (2022)
Repair	Repair and refurbishment of EV LiBs are often used interchangeably or in the same context and no clear definition exists of either. During refurbishment or repair, faulty modules are replaced to enable the remaining capacity of other modules which could be used for additional application.	Ahuja et al. (2020), Yang et al. (2021), Zhao et al. (2021b)
Refurbish	It is worth noting that refurbishment of EOL EV batteries is scarce and an established market for remanufactured batteries does not yet exist (Kastanaki and Giannis, 2023; Schulz-Mönninghoff and Evans, 2023)	Börner et al. (2022), Zhao et al. (2021a)
Remanufacture	Remanufacturing could be described as a combination of repair and reuse in which faulty or depleted modules are replaced within the battery pack to utilize the remaining capacity and rebuild it to be as close to its original specifications.	Börner et al. (2022)
Re-purpose	Re-purpose refers to the use of EV LiBs for an alternative application such as a stationary energy storage system. One of the main benefits of repurposing is that it postpones expensive recycling processes and battery disposal (Canals et al., 2022; Jiao and Evans, 2016)	Börner et al. (2022)
Recycle	Recycling in the context of EV LiBs at end-of-life refers to the process where discarded batteries are collected, processed, and broken down to recover valuable materials which then serves as a feedstock for the production of new products or materials	Alamerew & Brissaud (2020)
Recover	Recovery refers to the retrieving valuable battery materials such as Cobalt and Nickel after recycling	Zhao et al. (2021a)

Within the Australian context, stakeholder's agree that most materials present in EV LiBs are hazardous to the environment and human health if disposed incorrectly (Zhao et al., 2021a). Additionally, cobalt is considered as a toxic element and lithium is flammable if incorrectly handled (Yang et al., 2021). Hence, this calls for a need to develop a solution to effectively reduce adverse effects to the environment and its resultant implication to human health. Another perspective to consider is that new EV purchases in Australia nearly doubled from 2.1% in 2021 to 3.8% in 2022 (Whitehead, 2023). Hence, the increasing demand for EVs will inevitably lead to a larger amount of EV LiBs being disposed of to landfills. Implementing a stewardship scheme enables the industry to account for batteries ending up in scrap yards and facilitating the potential for second life applications as stakeholders are held responsible for proper EOL management of EV LiBs (Battery stewardship council, 2023). Currently, consultations for an industry led stewardship scheme in Australia is on-going with CE among one of the priorities (Battery stewardship council, 2024). Moreover, adopting a CE approach to the LiB industry as a solution can potentially save the Australian economy around $3 billion (Gentilini & Salt n.d.).

The significance of a CBM for EV LiB waste has been addressed by Reinhardt et al. (2020) whose research indicates that there is a need for stakeholders to form a multi-collaborative and holistic approach for the global issue of LiB waste. To improve the quality of data on CBMs it is necessary to adopt this comprehensive view as most activities such as dismantling, segregating and cost structure required at EOL for an EV LiB are interconnected (Wrålsen et al., 2021), while expectations and influences of stakeholders can be diverse (Albertsen et al., 2021). Recommendations made by different authors (Dokter et al., 2021; Hina et al., 2022; Konietzko et al., 2020) highlight the need to develop these key factors based on a multi-stakeholder perspective on how business models (BMs) can function within the slow and closed loops across multiple lifecycles. On the context of gaining a multi-stakeholder perspective on CBMs for EV LiBs, various authors have primarily included perspectives from academia, manufacturers, battery second use stakeholders and recyclers and to a lesser extent from government and not-for-profits (Albertsen et al., 2021; Chirumalla et al., 2022; Olsson et al., 2018; Schulz-Mönninghoff and Evans, 2023; Toorajipour et al. 2022; Wrålsen et al., 2021).

The literature on CBMs for EOL EV LiBs is still scarce and most of the research found in the literature originates from a European context (Albertsen et al., 2021; Chirumalla et al., 2022; Olsson et al., 2018; Wrålsen et al., 2021). Similar reference has been made in the study conducted by Chiappetta et al. (2020) who found that the majority of CE related research originating from the EU and Asia have a paucity of data on the Australian context. Moreover, current studies on CE and CBMs for EV LiBs are still being considered as broad, conceptual, and unclear (Bonsu, 2020; Chirumalla et al., 2024; Dokter et al., 2021). However, research has shown that CBMs can be context-specific (Albertsen et al., 2021) and the extent to which CE can be embedded in an existing business model is dependent on context-specific regulatory and cultural-cognitive factors (Levänen et al., 2018). Similarly, Kastanaki and Giannis (2023) claimed optimised management of EOL EV LiBs is achieved through planning at a geographical level to guide decision makers in successfully implementing CE initiatives. Evidence of this claim can be found in the study by Chirumalla et al. (2024) who suggest product and market variability among different industries as the main reason. Along the same lines, Asgari and Asgari (2021) claim the smooth transition to CE relies on a balance between various BMs within a specific context. Hence, there is a need to further understand the different actors in the EV LiB value chain along with the current BMs and their shift towards a CBM in a context-specific environment.

Currently, literature on CBMs for EV LiBs primarily focus either on recycling or repurposing from a technical or economic aspect (Wrålsen et al., 2021). This implies a lack of consideration on the broader definition of 'value', by predominantly focusing on the technical and economic gains rather than social and environmental gains. Additionally, the development of an appropriate CBM for EV LiBs needs to consider a broader list of R strategies. Hence, the aim of this research is to understand the Australian context and investigate the system-specific factors influencing the development of a suitable CBM.

To achieve the objective of this research project, this article is structured into nine sections. Section 2 provides a literature review on CE and CBMs from a generic perspective. This is followed by reviewing the development of CBMs in different contexts subsequently leading to the development of CBMs for EOL EV LiBs. This paper then presents the research approach and method in Section 3. The findings were analysed thematically based on an inductive approach and are presented in Section 4. These findings include presenting the flow of EV LIBs in Australia (section 4.1), context-specific barriers and drivers for developing a CBM for EOL EV LiB in Australia (section 4.2 and section 4.3 respectively).

The findings are presented using illustrations and quotes wherever necessary. This paper then discuss these findings to address the main objective of this article and investigate its consistency with the literature emerging from a European context in section 4.4. This is followed by providing theoretical and practical implications of the research study in section 5.1 and finally concluding remarks are presented.

2. Literature review

2.1. Circular economy (CE) and circular business model (CBM)

A CE is based on a restorative design where products, materials or components are kept at their highest value or utility at all times (Geissdoerfer et al., 2020). Complementing this definition, the Ellen MacArthur Foundation (EMF), defines CE based on three design principles; 1) regenerate natural systems, 2) keep products and materials at their highest value and 3) minimize waste and pollution (Ellen MacArthur Foundation n.d.). CE implementation takes place at micro, meso and macro levels of an economy, with the micro level considering how CE is implemented within businesses and households (Nobre and Tavares, 2021).

A business model (BM) is how an organisation generates value and can be understood as the design of business elements such as value creation, capture and delivery (Pieroni et al. (2019). Implementing CE in current BMs requires organisations to transition from a 'take-make-throw' thinking to a circular approach through which stakeholders can avail maximum value at EOL. This value can be recognized through developing BMs around the CE initiatives (Chirumalla et al., 2022) or CBMs.

The concept of a CBM can be defined as a business model to operationalise CE resulting in economic, environmental, and social value to all stakeholders (Albertsen et al., 2021; Wrålsen et al., 2021). CBMs act as a regenerative tool for developing a holistic system based on CE principles (Schulz-Mönninghoff et al., 2021), while narrowing, slowing and closing resource loops (Asgari and Asgari, 2021; Bocken et al., 2018; Galvão et al., 2022; Geissdoerfer et al., 2018 ; Oghazi and Mostaghel, 2018). Given the emerging concept of CE, organisations can gain a competitive advantage by generating new ideas and technologies while being complemented by a fitting business model (Olsson et al. (2018). The classification of different CBMs is dependent on the extent to which CE can be integrated in a business i.e. close or slow the loop (Vermunt et al., 2019) and each element/structure defines the kind of circular related activities a business can pursue and the extent to which CE can be incorporated.

The literature also indicates CBMs can be acknowledged as a specific category of sustainable BMs (Schulz-Mönninghoff and Evans, 2023; Wrålsen & Faessler, 2022). Hence, it is important to note terms such as CBMs and sustainable BMs are at times used interchangeably. Overall, the integration of CE into BMs is dependent on managerial strategies and ambitions but can mostly be classified as downstream (new revenue models), upstream (reverse logistics), and complete circular models (integration of upstream and downstream) (Pieroni et al., 2019). Similar classifications of CBMs can be found in the study by Chirumalla et al. (2024) and Hina et al. (2022) who broadly classifies CBMs into extending (repair, refurbishment, and maintenance for a second life); sharing (product-as-service and shared ownership); and looping (which refers to keeping the batteries in loop to retain maximum value).

Although most business models are developed with a perspective of a single product life cycle (Albertsen et al., 2021), a CBM is implemented through collaboration and co-ordination of inter-dependent/multiple stakeholders from multiple perspectives CBMs encompass multiple concepts and should involve a systems thinking approach if they are to be effective Chen (2020), Antikainen and Bocken (2019), and Dokter et al. (2021). The design of a CBM also introduces new variables from environmental and social aspects that must be considered from a systematic and dynamic approach (Pieroni et al., 2019), so remains a global challenge in transitioning to CE (Brown et al. 2020). Moreover, organisations lack the element of social inclusion and collaboration for high-value CE strategies such as remanufacturing and repurposing (Hina et al., 2022; Schulz-Mönninghoff and Evans, 2023). This calls for the development of a standardised CBM framework for implementation which is still scarce (Schulz-Mönninghoff and Evans, 2023).

2.2. Development of a CBM in different contexts

Evidence suggests that CBMs are context specific and must be developed and analysed in a specific manner (Albertsen et al., 2021; Lüdeke-Freund et al., 2019). The specificity of context could vary based on geographic region, the industry sector and the time period being considered. For example it has been found that the waste management sector identified recycling as the most financially lucrative business models (Ranta et al. 2018), while in the EV LiB sector, recycling is seen as a costly process (Lima et al., 2022; Schulz-Mönninghoff and Evans, 2023).

Hina et al. (2022) stated that to successfully implement CBMs in businesses, it is of critical importance to understand the different drivers and barriers. Additionally, businesses need to address their respective barriers prior to attaining their value creation goals. The drivers and barriers can be classified as those acting internally (hinderances or strengths emerging from within an organization) and externally (hinderances or strengths arising from outside an organization). However, delivering high quality products as per customer expectations is a major driver for businesses and remains constant despite integration of CE to BMs. This can be justified with the rationale that business' are generally profit driven (Pieroni et al., 2019). This also resonates with the recommendations made by Schulz-Mönninghoff and Evans (2023) whose research stated that the key criteria for businesses to gain a competitive advantage is the use of customer-oriented tools while developing a CBM.

The major barriers to introducing CBMs in organisations include lack of clear arguments for businesses and customer engagement, gap/s in role/s and relevance of CBMs and the lack of social and environmental considerations such as improving the quality of life beyond just economic gains and ecological impacts through mining or manufacturing (Lüdeke-Freund et al., 2019; Schulz-Mönninghoff and Evans, 2023; Schulz-Mönninghoff et al., 2023). Research has shown that these drivers and barriers can be context specific (Tura et al., 2019; Vermunt et al., 2019) and hence, business concepts which prove to be successful for one industry may fail for another (Hina et al., 2022; Tura et al., 2019). A prime example is that many of the case studies found in the literature were based on nickel-manganese-cobalt (NMC) batteries which consists of high value materials such as nickel, cobalt and manganese (Schulz-Mönninghoff and Evans, 2023; Schulz-Mönninghoff et al., 2023; Wrålsen and O'Born, 2023).

While LiBs generally are of two types: nickel-manganese-cobalt (NMC) and lithium ferro-phosphate (LFP), it can be seen that the dominant chemistry type for EV applications remains NMC in Europe (Kastanaki and Giannis, 2023; Schulz-Mönninghoff et al., 2023) with NMC 955 expected to dominate the market share by 2030 (Kastanaki and Giannis, 2023; Wrålsen and O'Born, 2023). However, current market trends are shifting to a cobalt free chemistry such as lithium ferro-phosphate (LFP) (Zhao et al., 2021a) as they possess better thermal stability (Ali et al., 2021). In 2022, the most popular car model sold in Australia was the Tesla Model 3 (Whitehead, 2023) which uses LFP batteries (Rustamov et al., 2022). Research demonstrates that unlike NMC, materials present in LFP constitute a lower value and hence have a poor market for recycling (Lima et al., 2022; Zhao et al., 2021a). However, many of the case studies found in the literature were based on NMC type batteries relative to LFP (Schulz-Mönninghoff and Evans, 2023; Schulz-Mönninghoff et al., 2023; Wrålsen and O'Born, 2023). Therefore, this requires more regulatory intervention and a robust recycling infrastructure accommodating varying LiB chemistries including NMC and LFP.

It can also be argued that the preferred pathway for an EV LiB at EOL is dependent on factors such as demand for raw materials, collection rates, safety concerns and economic value of individual materials (Albertsen et al. (2021); Lima et al. (2022). Hence, it is essential to take into consideration the stakeholder's perspective of the value chain and current market scenario for an EV LiB. This illustrates that it is vital for research focus on the actors of CE and that inter and intra organizational collaboration is still seen as a major barrier (Schulz-Mönninghoff et al. (2023). Hence, this research included stakeholder groups from not only manufacturers, but also remanufacturers/repurposers/recyclers, governments, researchers, not-for-profit organisations, and other relevant stakeholders. Thereby, gaining a holistic understanding of the drivers and barriers for development of a CBM for EOL EV batteries specific to the Australian context.

Another consideration is the role of the government in the development of CBMs for EV LiBs. Literature has shown that the government is the most important stakeholder in the context of developing CBMs for LiBs (Wrålsen et al., 2021). Similar indications supporting this finding can also be found in the literature (Kumar et al., 2021; Levänen et al., 2018; Lima et al., 2022; Rajaeifar et al., 2022; Sopha et al., 2022). Regulatory intervention is one such factor seen as a necessity to ensure data availability for CBM implementation (Schulz-Mönninghoff and Evans, 2023). The importance of regulatory intervention has also been stated by Islam and Iyer-Raniga (2022) and Tripathy et al. (2023), highlighting CE for LiB recycling. Furthermore, Galvão et al. (2022) concluded that CE is largely dependent on the regulatory sector. Presently, Australian federal policy such as the 'national battery strategy' was recently introduced with CE for batteries as one of their themes (Department of Industry Science and Resources, 2023). On the context of CE, the policy focusses on building an ethical battery value chain and supporting innovative technologies for battery recycling. Particularly, the government has allocated AUD $20 million to map the Australian battery value chain for future opportunities and AUD $7 million in the form of tax incentives for critical material processing for downstream operations from July 1, 2027 implying incentives directed towards recycling initiatives (DISR, 2024). Despite the presence of regulatory policies in Australia, it can be argued that current factors for developing a CBM for EOL EV LiBs may differ due to varying political agendas and targets relative to a larger market such as the EU. Moreover, much of the CBM literature for EV LiBs emerge from a European context based on the EU battery directive reflecting targets and standards adopted in the EU.

2.3. CBMs for EOL EV LiBs

CBMs for EV LiBs have been classified in multiple ways. Agrawal et al. (2021) classifies CBMs for EV LiBs based on the extent and inclusiveness of actors and circular related activities in the EV LiB value chain, while Olsson et al. (2018) classifies CBMs for EV LiBs based on four scenarios: 1) use in EVs + current recycling; 2) use in EVs + enhanced recycling; 3) use in EVs + repair and reuse in EVs; 4) use in EVs + repair and repurpose in energy storage systems. Generally, CBMs for EOL EV LiBs can be classified based on the four common 'R' strategies of CE-refurbish, remanufacture (reuse in EVs), repurpose (reuse in energy storage applications) and recycle (Chirumalla et al., 2022; Kastanaki and Giannis, 2023; Rajaeifar et al., 2022; Schulz-Mönninghoff and Evans, 2023; Schulz-Mönninghoff et al., 2023; Wrålsen and O'Born, 2023). However, it is more relevant to use the 10R framework to classify CBMs as this is more holistic approach to adopting CE. These are represented based on the order of preference (Cramer, 2017) as listed in Table 1.

In the context of developing a CBM, the business model canvas is the most common tool used for conceptualizing a CBM (Daou et al., 2020; Salvador et al., 2021; Sopha et al., 2022). Life cycle analysis (LCA) has also been found to be a valuable tool to support CBMs (Schulz-Mönninghoff and Evans, 2023; Wrålsen and O'Born, 2023) specifically in the case of battery repurposing (Wilson et al., 2021). A standard framework for implementing a CBM is scarce and viewed as a threat by managers as it indicates the replacement of existing business models (Schulz-Mönninghoff and Evans, 2023). Furthermore, clarity on the various responsibilities of business processes for ensuring material circularity within an organization is also lacking, along with roles associated for CE oriented actions (Chirumalla et al., 2022; Schulz-Mönninghoff et al., 2023). Another business solution that has gained prominence is the servitisation model or leasing platforms where automotive original equipment manufacturers (OEM) retain ownership of the battery by leasing it to their customers (Ahuja et al., 2020). The benefits of this solution include the increasing the number of EV batteries in use (Sopha, Purnamasari and Ma'mun (2022) and for repurposing in energy storage systems (ESSs) (Zhao et al., 2021a). However, despite the benefits of adopting service-based CE business models, it still requires additional investigation on hoe best to implement it (Schulz-Mönninghoff and Evans (2023).

Research on CBMs for EOL LiBs in EVs is still in its nascent stages and either focuses on recycling or second use application (Chirumalla et al., 2022; Islam and Iyer-Raniga, 2022; Wrålsen et al., 2021). However, the overall consensus dictates that EV batteries first be repurposed and then recycled to support sustainable, economic and environmental outcomes (Ali et al., 2021; Chirumalla et al., 2022; Schulz-Mönninghoff et al., 2021; Schulz-Mönninghoff and Evans, 2023; Vu et al. 2020). Current CBMs found in the literature are still considered conceptual (Schulz-Mönninghoff and Evans, 2023; Schulz-Mönninghoff et al., 2023) and are seen as an extension of the current value chain. However, it is interesting to note that most of the research on CBM for EV LiBs emerges from a European context where it has gained popularity as an emerging field of research (Albertsen et al., 2021; Levänen et al., 2018; Olsson et al., 2018; Wrålsen et al., 2021). Collectively, these studies reviewed outline a critical role for developing a CBM considering wider stakeholder perspectives and current market forces. Therefore, this research addresses the lack of research for developing a CBM for EOL EV LiBs in the Australian context by understanding the life cycle of an EOL EV LiB in Australia and thereafter understanding the key drivers and barriers which need to be considered when developing a CBM.

3. Method

The exploratory design of the study relied on semi-structured interviews to obtain industry specific knowledge from experts working in the LiB area in Australia and a qualitative approach was used for the analysis. Ethics approval for this research was obtained from the university's Human Research Ethics committee.

3.1. Data collection

Participants for the interviews were recruited from five broad categories, which play an influential role within the EV LiB sector (Olsson et al., 2018; Zhao et al., 2021a). These groups were: 1) automotive manufacturers, 2) recyclere/repurposers/remanufacturers, 3) government institutions, 4) researchers and 5) not-for-profits and other community organisations.

As this was an exploratory study, a sample size of 15–20 participants was aimed for, to obtain a broad range of information with relevant experiences related to the area of research (Yin, 2015). This range was selected based on the methods adopted by Chirumalla et al. (2024), King and Boxall (2019) and Zhao et al. (2021a). Initially, participants were identified through grey literature and professional networking platform i.e., LinkedIn. In the context of CBM for EOL EV LiBs, given the recent uptake in EV sales and emerging Australian LiB industry (Accenture, 2021), snowballing technique was also used to increase the number of respondents and acquire a comprehensive view of the EOL EV LiB scenario is Australia.

A total of 22 participants were interviewed (Table 2) The interviews were conducted in the last quarter of 2022 which lasted between 20 and

Table 2
De-identified Codes of interviewed participants (Source: Authors).

Group	Code	Affiliation	Experience in the relevant group
Manufacturer	M 1	EV manufacturer	More than 4 years
Manufacturer	M 2	EV manufacturer	More than 3 years
	M 3	EV manufacturer	More than 2 years
Recycle – Repurpose – Remanufacturer	RRR 1	EV battery remanufacturing, repurpose and recycle	More than 5 years
Recycle – Repurpose – Remanufacturer	RRR 2	EV battery repurpose and recycle	More than 2 years
Government	G 1	Victorian government	14 years
	G 2	Victorian government	8 months
Government	G 3	Victorian government	1 year
Government	G 4	Victorian government	Less than 1 year
Government	G 5	New South Wales government	18 months
	G 6	New South Wales government	18 months
Not-for-profit/other	NFP1	LiB related not-for-profit organisation	10 years
Not-for-profit/other	NFP 2	Battery manufacturing industry	12–13 years
Not-for-profit/other	NFP 3	LiB related not-for-profit organisation	5–6 years
Not-for-profit/other	NFP 4	EV advisory organisation	Less than 6 months
Not-for-profit/other	NFP 5	Government affiliated body	8 years
Not-for-profit/other	NFP 6	LiB related not-for-profit organisation	5 years
Not-for-profit/other	NFP 7	Battery consultant	More than 1 year
Researcher	R 1	University	6–7 years
Researcher	R 2	University	1.5 years
Researcher	R 3	Research organisation (LiB related)	More than 30 years
Researcher	R 4	Research organisation (LiB related)	5 years

60 min. Three pilot interviews were undertaken to assess duration of interview, clarity, order, and approach of the questions. The interview questions were refined based on the feedback received in the pilot stage which are provided in Appendix A.3.

3.2. Data analysis

Thematic analysis was used as the primary method of analysis to facilitate the emergence of themes or patterns arising within the interview data. This method has been used extensively in previous research within this area (Bonsu, 2020; Chirumalla et al., 2024; Reinhardt et al., 2020; Schulz-Mönninghoff and Evans, 2023; Toorajipour et al. 2022). The process of developing themes from the interview data included five stages. These stages consisted of compiling (arrangement of data in an informal order), disassembly (breaking down data into smaller fragments i.e., codes), reassembly (re-organisation of fragments into groups or sequence), interpretation (interpret sequences or groups) and conclusion (developing an overarching statement or themes based on the interpretation) (Yin, 2016). Prior to generating the codes, the data was compiled in an informal manner as part of stage one. Stage two was an iterative process where the recorded data constantly underwent a trial-and-error method to identify codes (Sekaran and Bougie, 2016; Yin, 2016). Stage three of the analysis validated the declaration made under the ethics protocol, where data acquired from participants was presented in a consensus to maintain anonymity.

As this research was explorative in design, an inductive approach was used for the thematic analysis. An inductive approach helps to uncover new themes, which may not have been adequately cited in the literature (Dokter et al., 2021; King and Boxall, 2019). The recorded transcripts of the interviews were transcribed and coded using NVivo 12, these codes were used to identify various themes and patterns after undergoing many iterations. The identified themes resulted in providing an overview of the EOL EV LiB life scenario in Australia along with the drivers and uncertainties related to CE and CBMs for EOL EV LiBs in the Australian context which are presented and discussed in the following section.

4. Findings and discussion

4.1. EOL EV LiB scenario in Australia

To provide a clear understanding of the current process influencing the development of a CBM for EOL EV LiBs in Australia, manufacturer group and recycler-repurpose-remanufacturer (RRR) group participants were asked to state the life cycle of an EOL EV LiB in their respective organization. Fig. 1 illustrates the actual flow of EOL EV LiBs in Australia, the different stages it encounters, and the stakeholders involved.

In the first row (EV LIB first life), after their application in EVs, while EOL EV LiBs are collected via local dealerships, there is still a possibility that they could end up in scrap yards due to insurance claims and accidents. However, manufacturer group participants are working with insurance stakeholders to reduce the likely event of EV LiBs being disposed of to landfills. However, M1 stated:

> *"For vehicles that don't come back to us for any reason … vehicles that have reached end of life … [and] typically end up in scrap [and] salvage yards …, we have a recommended practice on what to do with the batteries [in such instances]".*

Referring to the second row (EV LiB second life), it was also found that while dismantling, testing and segregation are done by the EV manufacturers, third party stakeholders offer similar services prior to handing off EOL EV LiBs to the recycler or repurposer. This is possible due to partnerships and collaborations formed with EV manufacturers, local governments, and battery-related peak-body organisations to create a circular network for EV LiBs. Similar partnerships have been formed by recycler-repurposer-remanufacturer (RRR) stakeholders, where a take-back system has been implemented to acquire the battery packs for recycling after their second life in ESSs. However, four participants stated that recycling in Australia is still limited to the material separation and formation of black mass (chemical components of batteries), which is then exported overseas for further treatment which can be seen in the third row.

On the context of ownership, the conditions of procuring EOL EV LiBs at every stage differs from each stakeholder and is dependent on the contractual agreements made by the EV manufacturers. However, one EV manufacturer stated that they are limited by insurance providers, who in the event of accidents, could physically own the EV LiB which hampers the CE goals of the organization. Another interesting finding was a recommendation made by M2 to co-locate reprocessing facilities that undertake EOL processes due to the geographical locations of major cities in Australia. This finding reflects those of Lima et al. (2022) and Yang et al. (2021) who also found that the economic aspects of recycling can vary depending on where the reprocessing plant is located.

In summary, Fig. 1 illustrates the current scenario of EOL of EV LiBs in Australia. While there are CE activities in Australia, it is useful to highlight the gaps and opportunities in the Australian context to create a closed loop circular network. The most common gap based on the participant responses is the lack of volume of EV LiBs at EOL in Australia. Moreover, collected EV batteries get exported overseas after supposed 'recycling' which accords by the findings of King and Boxall (2019). This highlights that even though stakeholders mentioned recycling taking place, it may actually refer to separation of material, and not the physical recycling process. Literature has shown that LiB recycling

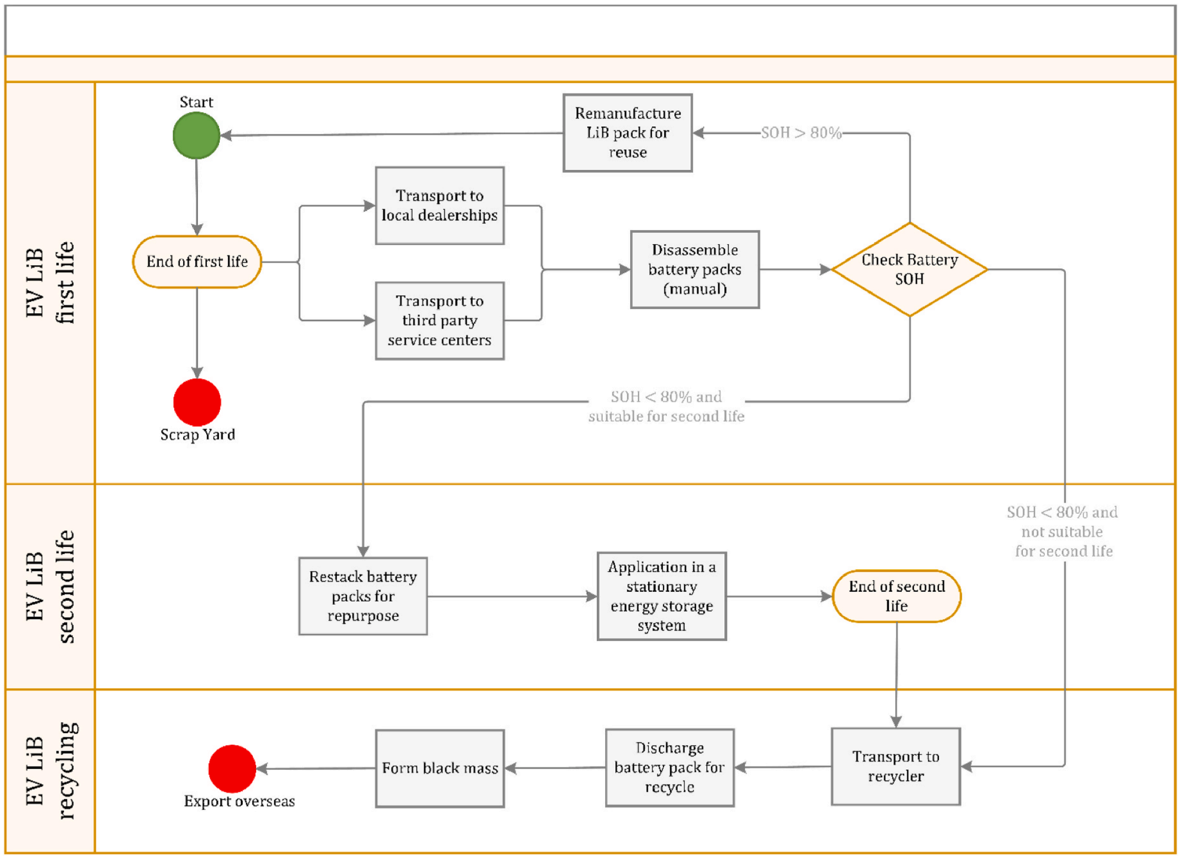

Fig. 1. Actual EOL EV LiB flow in Australia (Source: Authors).

rates remains at 3% in Australia (Langdon et al., 2023). Hence, it is safe to imply a closed loop CE does not currently exist in Australia. However, it is encouraging to note, Australia has the mineral resources most commonly used to produce EV LiBs (Collis et al., 2023), and therefore could have the fundamental expertise and knowledge for recycling to be carried out. Additionally, although immature in the present scenario, the findings of this research project provide support for potential recycling opportunities for EV LiBs. Taken together and referring to Fig. 1, these opportunities imply the need to develop a CBM considering the context-specific barriers and drivers in Australia.

4.2. Barriers for developing a CBM for EOL EV LiBs in Australia

Barriers are defined as the factors that hamper the implementation of CE for EV LiBs (Sopha et al., 2022). An in-depth detail of these barriers can be found in Appendix A.2. Although 13 categories of barriers were identified based on the thematic analysis, the three most influential barriers are discussed below. The criteria for identifying these major barriers were dependent on the number of participant responses and interrelationships between them. For example, barriers such as the lack of stewardship schemes, government incentives and regulatory policies were primary concerns among participants contributing to the lack of financial benefits, technical concerns, and lack of safety as additional barriers.

i. Lack of volume of EOL EV LiBs in Australia

This study found that more than half of the participants reported the lack of volume of EOL batteries to be the major barriers for the development of a CBM for EV LiBs in Australia. The lack of volume corresponds not only to the slow uptake of EVs in Australia, but also since Australia is a much smaller market relative to the EU leading to low numbers of EV use. In relation to the volume of EOL EV LiBs, R3 stated that:

> *"The immediate concern is whether we have the volume and if there's many of this activity happening simultaneously, then do we have enough volume because there's more process hunting for their waste material and you get the process set up, but you don't have a feed material to feed your plant".*

ii. Lack of supporting regulatory policies

Regulatory barriers were reported to be a major barrier in the development of a CBM for EOL EV LiBs. Particularly, participants referred to the lack of product stewardship schemes, lack of government incentives, lack of mandatory targets and a lack of a clear framework. At the time of conducting the interviews, the federal policy on the National EV strategy was undergoing consultation. However, one participant mentioned that this policy lacks direction and that it is currently focusing on the increase in uptake of EVs rather than developing a holistic approach. The policy at that time was still undergoing revisions and its effects on the Australian battery industry are yet to be seen. Participants referred to the lack of homogeneity in the state policies in Australia and stakeholders operating in silos contributing to barriers such as difficulty in transporting LiBs and the lack of collaboration. Participant G3, in response to the regulatory barriers stated:

> *"I guess in Australia, its state based, managed more state based with state-based policy instead of as a federal level and you could see that as a bias cause if one states allows them to be going to landfill and the others know … then people go to the cheapest solution".*

iii. Lack of knowledge and understanding on CE and CBMs

The lack of knowledge and awareness on the development of a CBM for EOL EV LiBs received considerable attention. Participants mentioned that stakeholders lack a proper understanding of CE and that there is less awareness on this concept. This can explain why stakeholders have developed a narrow perception on BM elements such as value capture and delivery. To highlight the importance of knowledge and awareness, R1 stated:

" …. there's a lack of knowledge like in terms what are the opportunities, the concept of product stewardship, which is a key approach for driving circular or implementing circular economies. Even the concept of circular economy is not well understood in business".

Although the lack of knowledge and awareness was reported to be a critical barrier, participants mentioned that part of the reason was that there are a lot of unknown variables for the concept of CE or CBM for EV LiBs to which participant NFP/O 2 stated:

"Every week, we are seeing a new challenge in this space and we're seeing that because it's never been done before and there's a lot of aspects to setting up circularity for batteries. They just aren't known until you get to the first time that you experienced that problem and then you go … ohh … OK, Now I need to deal with this and it was never thought of in the outset"

This illustrates that this is a typical "wicked problem", where stakeholders would need to take a transdisciplinary and holistic approach to solving this problem. In addition to increasing understanding of CE, stakeholders and policymakers will benefit from using a systems thinking approach rather than a piece meal approach, as is seen currently. The lack of holistic systems view of the problem can also explain why Australia is dependent on the EU and other nations and is adopting a 'reactive approach' for the development of a CBM rather than a 'proactive approach'.

Overall, the three major barriers were found to significantly influence other reported barriers by participants. For instance, barriers such as the lack of stewardship schemes, incentives and policies were primary concerns among participants relating to financial, technical and the lack of safety considerations as additional barriers. Another theme identified was that factors hampering CE growth from within an organisation (internal barriers) vary based on stakeholder perception. For instance, approximately 2/3rd of the participants claimed the importance of internal factors were irrelevant as they were fully immersed in CE. A minority claimed that this is dependent on the leadership and direction of the company, while the remainder claimed this is dependent on the maturity of the company.

Further analysis revealed these barriers can also be classified as factors that hamper recycling or repurposing EOL EV LiBs in Australia. The popularity of recycling and repurposing among participants for EV LiBs could be attributed to the emergence of battery energy storage systems in Australia (Collis et al., 2023) along with current recycling initiatives. Hence, a major theme developed from the resulting barriers included those attributed mainly to factors preventing recycling and repurposing EOL EV LiBs in Australia.

4.2.1. Barriers hampering recycling of EOL EV LiBs in Australia

Table 3 provides a list of these barriers for recycling EOL EV LiBs in Australia which have been categorised using PEST analysis. PEST analysis was used based on the selection of King and Boxall (2019) to strategically explore and understand the Australian context for LiB recycling. It was observed that recycling of EV LiBs in Australia is considered as an immature market mainly due to lack of volume, regulatory policies, and recycling infrastructure. The lack of recycling infrastructure is also one of the reasons why much of the dismantling of EOL batteries is labour intensive (Rajaeifar et al., 2022). While participants were in favour of the use of cobalt free batteries such as LFP, the growing presence of LFPs in Australia led participants to express their concerns regarding the poor economic value of recycled materials. Specific to the recycling of LFP batteries in Australia, G2 stated:

Table 3
Barriers for recycling EOL EV LiBs in Australia (Source: Authors).

Barriers for recycling EOL EV LiBs in Australia	
Category of barriers	Description
Political	Lack of data transparency to protect IP
Economic	Lack of market awareness
	High initial investment
	Cost of technology and infrastructure
	Cost to recycle LFP batteries
	Cost of sorting LiBs
	Poor economic value for LFP batteries
	Low economic value for recycling LiBs
Social	Lack of knowledge on recycling different LiBs
Technical	Manual disassembly
	Presence of cobalt in LiBs
	Presence of plastic or other materials
	Difficulty in recycling NMC batteries
	Batteries are not discharged prior to recycling
	Risk of fire due to thermal runaways in NMC batteries

"It's a cost to recycle. So, I'm not saying there's no value in it, but to recycle that battery, if you didn't have a gate fee, you'd lose money. With the NMC batteries, if you didn't have a gate fee, you would still make money because of the value of the Nickel and the Cobalt. But there's no nickel and cobalt in lithium iron phosphate. So, you know, you'd actually have to charge your gate fee or a price per kilo onto the LiPo batteries".

4.2.2. Barriers hampering repurposing of EOL EV LiBs in Australia

Repurposing of EV LiBs is also in its nascent stages in Australia. While many pilot initiatives are underway, the lack of volume and regulatory interventions was reported as its major concerns (Zhao et al., 2021a). Repurposed EV batteries are typically used in energy storage systems (ESSs). However, ESSs stakeholders prefer vanadium flow batteries and newer LFP batteries which offer longer life cycles and safety considerations (Accenture, 2021). Combined with the lack of market awareness, repurposing in Australia is not considered as a profitable business scenario. Additional reported barriers for repurposing in Australia were found to be intellectual property (IP) concerns as brand reputation and ownership of IP were termed essential among participants along with a lack of standardization. Relative to recycling, RRR 2 stated that:

"When you are recycling, you know you've got that black matter that you need to extract and that's kind of a standard product, whereas for us, we need something … which we need to be standardized for our remanufacturer. But that's not what's happening through this repurposing industry".

Similar to recycling and referring to Table 4, it can also be found that most of the barriers to repurposing EV LiBs are also interrelated with the lack of collaboration and regulatory intervention. Hence participants often opt for the path of least resistance. In relation to this, RRR 2 stated:

"From my experience. I'm just gonna talk experientially. I think regulation is a terrible thing to say, but I think the big stick works better than the carrot in this instance. Yeah, people do collaborate, but in the end, they go down the path that's gonna be either least cost or they'll get some value through, you know, public relations. You know, I'd like to think that people would collaborate on this, but without a big regulatory stick, it's not going to move the needle".

4.3. Drivers for the development of CBM for EOL EV LiBs in Australia

Table 5 represents a list of drivers categorised using PESTLE analysis adopted and modified from King and Boxall (2019) and Kurdve et al.

Table 4
Barriers for repurposing EOL EV LiBs in Australia (Source: Authors).

Barriers for repurposing EOL EV LiBs in Australia	
Category of barriers	Description
Economic	Cost of sorting for reuse of battery modules
	Cost of LiBs for battery energy storage applications
	High initial investment
	Competition with flow batteries
	Competition with new batteries
Political	Preference of alternate applications
	Choice to recycle over repurpose to protect Ips
	Choice of ownerships
	Insurance claims
Social	Lack of market awareness
Technical	Varying design including different electrical contacts for different models
	Unpredictable state-of-health due to consumer driving conditions
	Lack of quality assurance

Table 5
Drivers for the development of CBM for EOL EV LiBs in Australia (Source: Authors).

Drivers for the development of CBM for EOL EV LiBs in Australia	
Category of Drivers	Description
Legislative	Introduce financial incentives
	Financially support proof of concepts, repair and repurpose operations
	Introduce targets to include recycled materials in battery production
	Promote extended producer responsibility and introduce stewardship schemes for EV batteries
	Government agenda on national security concern, technologies, critical minerals, and manufacturing goals
	Mandate standardization of batteries
	Mandate take-back schemes and data tracking for recycling
	National Electric Vehicle strategy
	Introduce procurement policies through government owned fleets
Social	Shared understanding and awareness of the EOL scenario for all stakeholders including consumers
	Knowledge on how to be involved in CE initiatives
	Education campaigns to nullify the 'second-hand' stigma
	Education to clarify benefits of CBM operations
	Knowledge on which R&D innovations stakeholders should support.
	Facilitate conversations across the supply chain and among interested stakeholders
	Facilitate the development of partnerships with research institutions
	Improving the overall health and stability of the society
	Facilitate market upskilling and creation of job opportunities
Economic	High value of materials such as nickel, cadmium, manganese, aluminium, and cobalt
	Profit driven CBM operation (What is my return on investment?)
Ethical	Leadership of the CEO or managing directors
	Organization culture to support CE initiatives
	Environmental, sustainability and governance (ESG) targets
	Brand reputation (sustainability image)
	R&D innovations in recycling and repurposing EOL EV LiBs
	Direction of the business to do the 'right thing'
Technical	Implementing design capabilities for disassembly, recycling and second life applications
Political	Global stability
	Influence of European countries and the U.S on policy settings and best practices such as:
	i Vertical Integration
	ii Third-party collaborations for reuse and recycle.
	iii Extended producer responsibility schemes
Other	EV uptake and forecast of volume of EOL batteries
	Charging infrastructure

(2019) for the development of CBMs for EOL EV LiBs in Australia emerging from the semi-structured interviews. Based on the thematic analysis, four major drivers have been presented as follows.

i. Possible regulatory changes

In contrast to the barriers, regulatory changes was reported to be the most important driver for the development of a CBM in Australia. Majority of participants reported the implementation of circular friendly procurement policies could result in the government introducing financial incentives and promoting standardization. This could be facilitated through government-initiated pilots using government owned fleets and involving multiple stakeholders promoting collaboration. Discussing the involvement of the government, participant R1 stated:

> *"There's an opportunity for the government to incentivize and encourage design changes and you know ensure that their incentive programs and funding programs are actually encouraging, innovation in product design as well as innovation in business models and that can be done through procurement …."*

> *"… … but you know, funding, research, funding deployments, driving scale up through procurement."*

It is also interesting to note that most participants agreed that financial incentives and investments are essential to commercialize proof of concepts and repurpose pilot operations. Federal policies such as the national EV strategy were also mentioned to play a key role in the uptake in EVs along with emphasis on extended producer responsibility. On a national level, one participant also mentioned that the current government goals on critical minerals and national security could also act as drivers as it will determine the amount of reprocessing that can be done in Australia and overseas.

ii. Increase in knowledge, understanding and collaboration

In addition to gaining knowledge on CE and CBM for EOL EV LiBs, participants mentioned knowledge on how to be involved in CE initiatives to be a key driver. This also relates to forming collaborations with research institutions as participants stated that the knowledge on the benefits of a CBM is lacking and that this could be a major driver to which participant NFP 6 stated:

> *"For us it is knowledge, we already have the knowledge of designing battery systems. We are in the field ….in the market, so we can supply them as well. But what are the enablers ….as well the enablers of other things is many, like if you're talking about circular economy in the battery …..so the benefits have to be made clear. Education needs to be there."*

In addition to gaining knowledge, all participants agree that collaboration is critical for the successful development and implementation of CBMs for EOL EV LiBs in Australia. Particularly, participants reported the effectiveness of collaboration can be achieved by facilitating conversations not only between the government and industry stakeholders but also with academics and research institutions. Discussing the significance of collaboration in overcoming barriers to repurposing EV LiBs in Australia, participant M1 stated:

> *"Everything comes back to collaboration … it is going to be important because you still have to find a market for the second life product".*

iii. Overseas drivers

Since Australia is a smaller market compared to the EU, external drivers such as global stability and influence of the European countries are significant drivers for the development of a CBM. Particularly, overseas stakeholders engaging in vertical integration and best practice method such as the extended producer responsibility policies (Albertsen et al., 2021). In businesses engaging in vertical integration, one participant mentioned that this could potentially increase the volume of batteries collected at EOL. An increase in volume of EOL batteries is directly proportionate to the commercialization of CE strategies. Thereafter, an important consideration to ensure its success is to formulate policies based on a holistic approach that supports the industry implementing various business solutions to which participant G2 alluded:

> *"For industry their model of operation is profit seeking around delivery of a service or good. So, they're operational model is to maximize profit and externalize costs. Whereas government must act in the interest of the people in the state, so they must look at the impact of externalized costs and figure out how to mitigate those costs and so circular economy results in a whole of system approach which is more reflective of the base ethic of government".*

Along the lines of increasing the volume of EOL EV LiBs in Australia, it was recommended that Australia could setup an EV battery processing Hub importing EOL LiBs from Asia to tackle the immediate barrier of low volumes of EOL LiBs to which participant G2 alluded:

> *"So, the only way to future proof that [feedstock of EOL EV LiBs] is stop the export of the material which I can't. You have to get a permit to export waste batteries and a lot of boats don't take lithium because of their fire risk and insurance risk. So, for the most part, what is in the country stays here but the only way to inject material volume now is to work out a pathway that we [Australia] would be a hub a reprocessing hub and bring material into Australia to reprocess [LiBs]."*

iv. Organisations ethical conscience drivers

In contrast to external drivers from overseas, internal drivers such as leadership of the organization, organization culture and ESG targets also play an important role. Participants mentioned that the direction and commitment of the organization to do the 'right thing' is essential for stakeholders to implement CE initiatives for EOL EV LiBs to which participant M1 stated:

> *"Ultimately, it comes down to the to the will of the company effectively because the easiest thing would be to ship them straight to a recycler and it's gone, it's out of the workshop. No one's looking at it. It just goes, gets recycled, whatever. That would be the easiest for an OEM perspective because your job's done at that point. It's probably not the right thing, probably not the best thing. And that's where I just think about that a bit deeper."*

4.4. Discussion

The goal of this research was to identify factors essential for the development of CBMs for EOL EV LiBs in the Australian context. This research study commenced by mapping the flow of EOL EV LiBs in Australia and found there is still a possibility of EV LiBs at EOL ending up in scrap yards. This finding is consistent with Baars et al. (2021) whose observations show EOL LiBs become lost in unknown locations even before reaching recycling facilities. Hence, the need for a CE for EV LiBs in Australia was justified among participants based on the understanding that LiBs are hazardous. However, the transition of EV LiBs resulting in CE needs a comprehensive understanding of the key factors, relevant stakeholders and strategies to ensure long-term benefits (Sopha et al., 2022). The key factors and strategies were identified by analysing the context-specific barriers and drivers on the development of CBMs for EOL EV LiBs in Australia. Overall, the analysis revealed the major barriers to the development of CBMs in Australia were the scarcity of volume of EV LiBs at EOL, inadequate regulatory policies and the lack of knowledge and understanding on the development of CBMs for EV LiBs in Australia.

These findings are similar to those of Sopha et al. (2022), Hina et al. (2022), Albertsen et al. (2021), Olsson et al. (2018) and Wrålsen et al. (2021) whose studies noted similar barriers including the lack of financial incentives and the lack of safety considerations. However, the findings of this study also show that there are many technical barriers for implementing a CBM in Australia mainly attributing to 'unknown financial viabilities' and 'unknown recovery values' for different chemistries. These technical barriers together with the high cost of transportation can lead to financial unviability. The high cost of transportation is mainly due to the geographical distance between major cities in Australia. This implies that although CE and CBM were positively viewed among participants, the specifics of implementing a CBM in Australia is seen as complex and unclear. This can be justified by reported barriers such as the 'emergence of unknown variables' and 'unknown rate of transition to EVs' due to a 'new and emerging industry' and a 'smaller market scenario' all of which are unique to the Australian market. This can also be attributed as to why recycling is considered as an immature market and repurposing is still in its nascent stages in Australia.

The lack of volume being identified as a major barrier for implementing CE shows that stakeholders are still viewing the EOL LiB problem from a linear economic and business model perspective. If the viability of a business model relies on increased volumes of waste, this is contradictory to basic CE principles, which is to eliminate waste generation in the first place. The expectations that increased waste volumes will make management of the waste more viable is more in line with assumptions within a recycling economy, which sits within a more or less linear system. If a CBM, which is fundamentally circular, is to be developed making it financially viable with low volumes of waste needs to be considered.

On further examining both repurposing and recycling opportunities in Australia, the presence of these 'unknown variables' implies a commercial risk for businesses investing in CE practices. Moreover, the analysis revealed that repurposed EV LiBs in Australia faces heavy competition with newer LFP batteries and vanadium flow batteries for application in energy storage systems. This was mainly due to the lack of safety considerations and low financial gains in repurposing EV LiBs based on the participant responses. This finding is somewhat contrary to that of Michelini et al. (2023) who found that repurposed EV LiBs offer the best solution in terms of application in energy storage systems (ESSs) as compared to flow batteries. Therefore, it can be implied that despite barriers being similar to those in the EU, how these barriers interact in a given context can be unique considering the Australian market. Contrary to repurposing, the presence of recycling LiBs was found to be greater in Australia. A possible explanation for this is due to the unpredictable state-of-health (SOH) which is irrelevant in the case of recycling EV LiBs. SOH is defined as the current maximum capacity to the capacity at what it is rated (Lin et al., 2023). Nevertheless, the lack of standardisation and high cost of transportation as reported by participants poses difficulties for both repurposing and recycling strategies. However, it should be noted that recycling may refer to separation of material rather than complete recycling.

The introduction of financial incentives through procurement policies and pilot initiatives by the government were mentioned as key drivers to mitigate the 'unknown variables' and commercial risks associated with CE practices in Australia. This is consistent with the findings of Wrålsen et al. (2021), which identified 'the government' being the most important stakeholder and that the intervention of government stakeholders are key to boost economic benefits (Albertsen et al., 2021; Lima et al., 2022; Zhao et al., 2021a). These findings also reflect those of Sopha et al., (2022) who found regulatory drivers appear to be dominant and comprehensive relative to other drivers for developing a CBM for EOL EV LiBs. A possible explanation for this relationship could be the lack of LiB manufacturing in Australia (Accenture, 2021) and exporting of waste battery materials overseas for further reprocessing (King and Boxall, 2019), which hampers repurposing and recycling initiatives in Australia. Nevertheless, the regulatory policies could incentivise the development of CBMs for businesses seeking a competitive advantage. Additionally, government-led initiatives which include pilot projects could be used to validate operations and cost structures implemented in the CBM under specific market conditions (Schulz-Mönninghoff and Evans, 2023). Presently, while CE appears to be a priority in the 'national battery strategy', future actions targeted towards reuse, remanufacture and repurposing of EOL EV LiBs are not yet made clear. This implies a gap of consideration from the 10R perspective of circularity for EOL EV LiBs in Australia. In the same vein, the research project indicated that while participants are aware of the complexities and opportunities of the battery industry and are willing to do the 'right thing', the awareness on 'how to get involved' is lacking. Particularly, the knowledge of 'which R&D innovations to be support' and 'how to be involved' would be a key driver to overcome the lack of consideration from a 10R perspective. This could also support the finding of a greater presence of recycling relative to repurposing in Australia.

However, the knowledge of 'how to be involved in CE initiatives' was not readily found and would be key in developing a viable CBM for EOL EV LiBs in Australia. This also explains why collaboration is vital to facilitate conversations among interested stakeholders and to develop partnerships with research institutions to maximize the value of a product (Bocken et al., 2018). This is supported by other studies confirming collaboration between academia, government and industry is critical to improve recycling (Beghi et al., 2023), drive CE strategies (Rajaeifar et al., 2022), ease dismantling and remanufacturing processes (Chirumalla et al., 2023) and enable data traceability (Gahlaut and Dwivedi, 2023) for EOL EV LiBs. Another implication of this finding can also be attributed to overcoming the perception of value mostly associated with gaining financial and economic value (Sairanen et al., 2024).

The benefits of undertaking CE initiatives for EOL EV LiBs in Australia were identified as to gain economic benefits and create new business opportunities (Refer Appendix B.1). This was found consistent with the literature (Nurdiawati and Agrawal, 2022; Olsson et al., 2018) and is justified given the lack of volume of EV LiBs at EOL to create a profitable business scenario for repurposing and recycling EV LiBs in Australia. It is then necessary to consider overseas practices such as 'vertical integration' and policies such as the 'extended producer responsibilities' to effectively create and deliver value through the development of CBMs for EOL EV LiBs. This is justifiable as the findings of this research show that Australia is influenced by overseas policies and practices. In light of this finding, the implementation of stewardship schemes for EV LiBs was widely supported by the participants of this research. While aligning with overseas practices is currently being considered in the upcoming stewardship scheme (Battery stewardship council, 2024), the proposed actions are subject to further consideration and discussion is on-going based on the challenges and opportunities in Australia. Nevertheless, based on the findings of this research, preliminary initiatives could include informing stakeholders on 'how to be involved in CE practices' and to develop a comprehensive view for the development of context specific CBMs in Australia.

This exploratory study therefore provides insights into the development of CBMs for EOL EV LiBs in Australia, which is twofold. First, referring to Fig. 1, the analysis of this research suggests that CBMs involving remanufacture and reuse of EV LiBs could postpone immature recycling and unviable repurposing in Australia. This implies the emergence of fewer 'unknown variables' and a reduction of overall processes. Secondly, engaging in partnerships with universities and research institutions can facilitate R&D contributions to redesigning EV LiBs to overcome the barrier of the lack of standardisation of EV LiBs. From a global context, these findings also suggest prioritising R strategies such as 'reuse' and 'redesign' against the common 3Rs (remanufacture, repurpose and recycle) dominant in the literature focusing on CBM classifications for EOL EV LiBs (Toorajipour et al., 2022). It is also interesting to note the EU waste framework directive proposes 4Rs (reduce, reuse, recycle and recover) which identify as four types of CBMs (Wrålsen et al., 2021). However, considering the present scenario of EV LiBs in Australia, this study proposes following the 10R strategy based on the order of prioritisation to not only understand and capture value but also consider the regional factors of developing a CBM. Hence, this research adds to the recommendations provided by Etxandi-Santolaya et al. (2023) whose study highlights a case-specific analysis to understand and prioritise circular processes.

5. Conclusions

5.1. Academic contributions and implications

The study provides academic contributions on CE and CBM for EOL EV LiBs. First, on the context of EV LiBs, many authors (Albertsen et al., 2021; Sopha et al., 2022; Wrålsen and O'Born, 2023) have found drivers and barriers related to CE and CBMs. However, a drawback observed was that most drivers and barriers related to the development of CBMs for EOL EV LiBs involved a lack of consideration on specific factors such as market conditions, geographical location, policy settings and product variability. Hence, this study presented drivers and barriers related to the development of CBMs for EV LiBs based on the Australian context. As such, this research found barriers such as 'unknown variables' and 'lack of homogeneity of state-based policies' and drivers such as 'influence of practices and policies adopted in the EU' to be unique to the Australian context. The research in this study therefore recommends researchers to further investigate these unique factors which could facilitate a comprehensive rich data on the development of CBMs.

Second, this research builds on the existing literature related to the development and classification of CBMs for EOL EV LiBs. The present study found a variation among authors in classifying relevant CBMs for EV LiBs as mentioned in section 2.3. Here, it was found that R strategies such as 'repurpose' and 'recycle' were commonly used to classify different types of CBMs. However, R strategies such 'reduce' and 'redesign' were not explicitly mentioned while classifying CBMs for EV LiBs. Additionally, although 'recycling' appears to be dominant, the principle of 'reduce' is interlinked with recycling and hence the principles involved in CE implementation become blurred as studies are based on the 4Rs, which is relevant to a recycling economy rather than CE. Hence, this research study recommends prioritising the 10Rs of circularity for the development of CBMs for EOL EV LiBs.

This study also has some managerial implications as it offers valuable insights to stakeholders currently planning to implement CE strategies for EV LiBs in their respective organisations. This research developed a model to represent the actual flow of EV LiBs in Australia as seen in Fig. 1 which highlights the current hurdles that need to be overcome to create a CE for EV LiBs in Australia. The different stages illustrated in Fig. 1, represent opportunities for stakeholders to participate and collaborate in the CE sector. For instance, stakeholders could collaborate to implement relevant stewardship schemes to avoid EV LiBs ending up in landfills as seen in Fig. 1 and discussed in section 4.4. Additionally, studies have shown the application of energy storage systems has seen a continual growth in the Australian context relative to the EV LiB industry (Accenture, 2021; Collis et al., 2023). Hence, a valid conclusion could be to develop CBMs focusing on repurposing EV LiBs to meet increasing market demands. However, this research study found that repurposing EV LiBs faces many challenges in Australia as discussed in section 4.2.2. Hence, this research suggests stakeholders consider alternative CE strategies proposed in Table 1 considering the current scenario as laid out in Fig. 1.

This research also highlights the importance of collaboration and taking a systemic approach to solving the EV LiB challenge. It emphasizes the involvement of academics and research institutions. Collaboration between industry and academia will alleviate the gap in knowledge on how to implement CE initiatives and help implement repurposing initiatives considering the volume of EV LiBs at EOL, industrial capabilities and market requirements. A systemic approach will require all relevant stakeholders being consulted and being involved in the design of circular solutions. From an Australian context it is vital to involve the insurance industry as current vehicle insurance policies and procedures have a major influence on EOL vehicles. If CE interventions are developed without consideration of procedures around insurance write-offs, it would be challenging to achieve higher order CE outcomes.

Our research has shown that influence of government policies plays an important role in the implementation of CE and CBMs for EV LiBs in Australia. Hence, this research provides recommendations to policy makers which may be of assistance to experts in the EV LiB industry. These findings suggest several courses of action for regulatory stakeholders –

1) A reasonable approach to tackle the issue of lack of volume of EOL EV batteries in Australia could be to investigate the impact of procurement policies and government led pilot initiatives. 2) On a macro level, the government could direct its focus not only on the initial stages (manufacturing, EV uptake, mining) but also to understand how to deal with the batteries and materials imported into the country at EOL. 3) A key policy priority could therefore be to support industry to co-locate reprocessing facilities to avoid transportation barriers and mitigate the un-homogenized state-based policies. 4) The findings of this study can be used to develop targeted regulatory interventions aimed at providing opportunities for industry to implement relevant CBMs for EOL EV LiBs. As such, further research should be conducted to determine the effectiveness of vertical integration and leasing platforms in similar market scenarios like Australia.

5.2. Conclusion and limitations

This research focused on exploring the factors relevant to develop CBMs for EOL EV LiBs in Australia. Based on the premise of literature mostly emerging from a European context and that research on CBMs for EV LiBs is scarce. This research study aimed to understand the expectations of relevant stakeholders by identifying context-specific drivers and barriers in Australia.

Subsequently, this research study discusses the findings and provided theoretical and managerial implications of this research to promote the development of effective CBMs for EV LiBs in Australia. As part of the findings, this research study developed an actual flow of EV LiBs in Australia and consequently highlighted the shortcomings related to the development of CBMs in Australia. Subsequently, three major barriers were found based on the thematic analysis - the lack of volume of EV LiBs at EOL, lack of regulatory policies, and the lack of knowledge and understanding on the development of CBMs for EV LiBs in Australia. The thematic analysis revealed barriers specific recycling and repurposing which shed light on the challenges associated with LFP batteries not readily found in the literature. Similarly, this research study found five contextual drivers for developing a CBM in Australia which included regulatory drivers through procurement policies and government-initiated pilots, the increase in knowledge, awareness, and a shared understanding, overseas drivers, internal drivers, and the increase in collaboration.

The key contribution to the literature from a global perspective is the understanding that the uniqueness of these factors varies depending on the influence of the major drivers and barriers found in this research. Factors such as 'unknown variables', 'dependence on the EU and other nations', and the 'lack of homogeneity of state-based policies' appear to be unique to the Australian context. The research findings also indicate that while stakeholders are aware of the complexities of implementing a CE in EV LiB industry, the knowledge on 'how to be involved in CE initiatives' was lacking and if this was overcome it could be a major driver in the development of CBMs for EOL EV LiBs in Australia. Additionally, this research study stresses on the importance of collaboration by facilitating conversations with relevant stakeholders and developing partnerships with research institutions which was also one of the key factors for developing a CBM for EOL EV LiBs in Australia. Another implication made through the findings is the need to develop and classify CBMs using the 10R strategy as opposed to the prevalent 3R or 4R strategy for EV LiBs. As such, this research study recommends focusing on R strategies such as 'reuse' (reuse LiBs in EVs), 'reduce' (reduction in overall process) and 'redesign' (innovate standardised EV LiBs) otherwise underscored in the literature related to classification of CBMs for EV LiBs. In doing so, stakeholders may be able to capture not only financial or economic value but also social and environmental value for EOL EV LiBs in Australia.

This research has a few limitations. First, as the EV LiB industry is still new and emerging in Australia, participants specifically affiliated to EV LiBs were extremely difficult to identify. Hence, participants affiliated to the broader LiB industry and familiar to the EV LiB were also included. This study also acknowledges the lack of EV manufactures, LiB manufacturers and second life stakeholders who may offer in-depth insights and comprehensive data on implementing CE for EV LiBs in Australia. Future research can include more stakeholders, which becomes easier as the EV LiB sector matures.

This research took a qualitative approach to identifying the influencing factors and did not analyse the interrelationships between these factors. As it was found that the different factors can influence each other research could focus on understanding the interdependencies and relationships of the major factors identified through this research. Such research could also include some level of quantification of the factors, to understand the relative importance of them.

Future research could also include gaining insights from insurance stakeholders on the implementation of stewardship schemes and take-back policies for EV LiBs at EOL. Lastly, an interesting prospect would also be to investigate the influence of digital technologies such as artificial intelligence and blockchain technologies on the contextual factors found in this research.

CRediT authorship contribution statement

Alston Furtado: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Usha Iyer-Raniga:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Rezaul Shumon:** Writing – review & editing, Supervision. **Akvan Gajanayake:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Professor Usha Iyer-Raniga reports financial support was provided by the Integrated Clean Energy, Circular Economy, and Climate Resilience Platform (IC3P) under the Victorian Higher Education State Investment fund. Alston Furtado has patent pending to RMIT University. There is no conflict of interest between the authors and readers. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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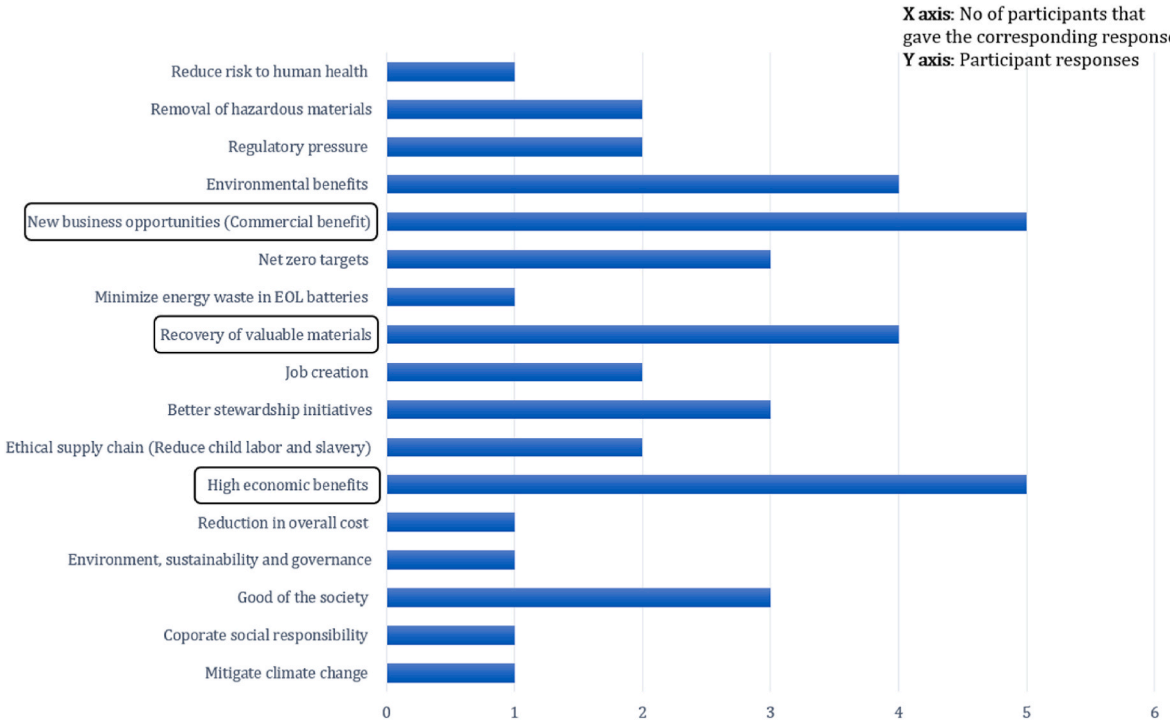
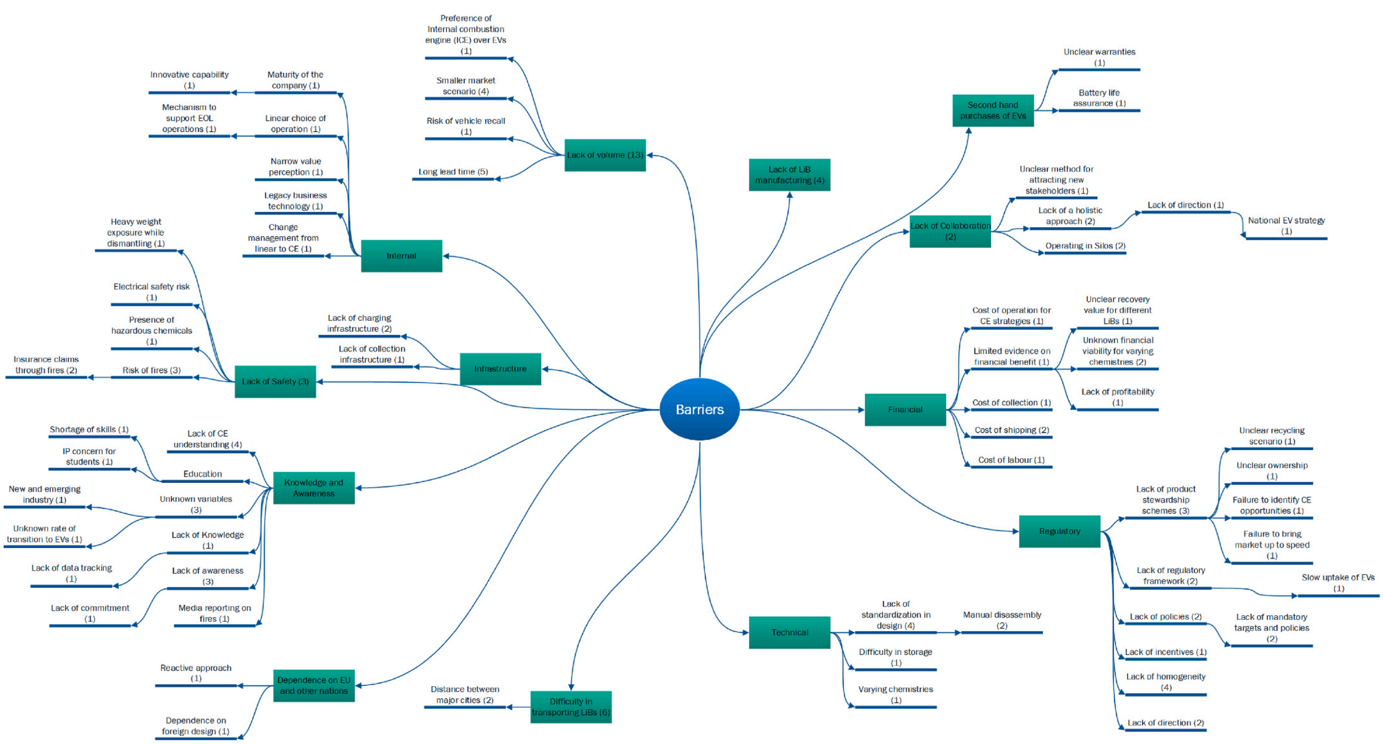
Appendix



Appendix B.1. Advantages on implementing CE for EOL EV batteries in Australia (Source: Authors).



Appendix A.2. Barriers for developing a CBM for EOL EV LiBs in Australia (Source: Authors).

Appendix A.2 presents the 13 categories of barriers found related to the development of CBMs for EOL EV LiBs in Australia. Each category entails additional sub - barriers based on the participant responses. The number of participant responses corresponding to each sub – barrier is also provided in brackets.

Appendix A.3. Interview protocol

i. The following research protocol was developed and intended for participants from the EV manufacturer group and recycle – repurpose – remanufacturer group.

Background of the participant and/or organisation.

1. What is your role within the organisation?
2. Can you please
provide an overview of the core business activities of your organisation?

Life cycle of EV LiBs at EOL in Australia.

3. Could you please describe the current life cycle of EV LiBs within your organisation?
4. How engaged are the activities of your organisation in the pre-processing stages of remanufacturing/repurposing/recycling? (For example - collection, segregation, discharge, or testing)
   - Are there any requirements prior to the activities you mentioned?
5. Does your organisation retain ownership of the battery or does the ownership still belong to the EV manufacturer?
6. Is your organisation involved in other CE related activities for EOL EV LiBs such as reusing etc.?

Expectations, drivers, and barriers to the development of CBMs for EOL EV LiBs.

7. What are the 'advantages' or 'value-addition' your organisation envisions to create by undertaking the CE activities mentioned?
8. What do you think are the main and immediate challenges related to the CE activities undertaken by your organisation for EOL EV LiBs?
9. What factors could contribute towards overcoming these challenges mentioned?
10. To what extent does the involvement of the federal government influence in resolving the mentioned challenges?
11. What role does forming partnerships between various relevant stakeholders represent with respect to resolving these mentioned challenges?

Perspectives and recommendations (if any) of participants on CE and CBM for EOL EV LiBs.

12. To what extent would you agree that CE for EOL EV LiBs is limited to recycling, repurposing, and remanufacturing of retired EV batteries?
    - What additional goals or targets, if any, should an organisation aim for?
13. Based on what we have discussed and on the context of CE and CBM for EOL EV LiBs, would you like to provide any other comment?

ii. The following research protocol was developed and intended for participants from the researcher group, not – for – profit/other group and government group.

Background of the participant and/or organisation.

1. What is your role within this organisation?
2. How engaged are the activities of your research or organisation in various CE strategies for EV LiBs at EOL?

Expectations, drivers, and barriers to the development of CBMs for EOL EV LiBs.

3. What 'advantages' or 'value-addition' do you envision for the industry undertaking CE activities for EOL EV LiBs?
4. What do you think are the main and current challenges that exist in the industry to adopt a CBM for EOL EV batteries?
5. What factors could contribute towards overcoming these mentioned challenges?
6. To what extent does the involvement of the federal government influence in resolving the mentioned uncertainties?
7. What role does forming partnerships between various relevant stakeholders represent with respect to resolving these mentioned challenges?

Perspectives and recommendations (if any) of participants on CE and CBM for EOL EV LiBs.

8. To what extent would you agree that CE for EOL EV LiBs is limited to recycling, repurposing, and remanufacturing of retired EV batteries?
   - What additional goals or targets, if any, should an organisation aim for?
9. Based on what we have discussed and on the context of CE and CBM for EOL EV LiBs, would you like to provide any other comment?

Data availability

The data that has been used is confidential.

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