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Exploring key factors to achieve circularity for end-of-life electric vehicle lithium batteries in Australia

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Abstract. Globally, there has been an increase in the production and deployment of lithium batteries (LiB). Specifically, this is due to the recent energy transition and electrification of vehicles. However, as the dependence of electric vehicles (EV) continue to increase, a large volume of LiBs are expected to reach end-of-life (EOL) in the coming years. The circular economy approach has been proposed for EOL EV LiBs to intensify the application of products and minimize waste. Circular business models (CBMs) act as a tool to implement this approach and create value-adding opportunities for businesses. However, research focusing on the development of CBMs from an Australian context is sparse. This research aims to explore the Australian context to achieve circularity for EOL EV LiBs from the perspective of key stakeholders within the value chain and identify key strategic outcomes to minimize the disposal of EV LiBs in landfill. The findings revealed that a lack of government policies is a major barrier to achieve circularity for EOL EV LiBs. Additionally, repurposing of EV LiBs faces a greater challenge than recycling. Hence, we propose adopting a repair + reuse + recycle CBM as a suitable outcome to mitigate the concern of EOL EV LiB waste considering the built environment context. Recommendations include involving stakeholders from the government and academia groups to explore the development of CBMs in Australia.

1. Introduction

The contribution of Electric vehicles (EVs) towards reducing CO_2 emissions of private transportation has been recognized by many researchers [1-4]. From a social and environmental perspective, the biggest contribution of an EV over a conventional vehicle is the reduction in noise and exhaust fumes during its operations [5]. It is forecasted that by 2040, around 70% of the automobile market share in the EU and 50% in China will comprise of EVs [2]. The recent trend estimates that approximately 77% of the globally installed LiBs will come from EVs in 2030 driven by the decreasing price of LiBs [6]. Subsequently, it is forecasted that around 250,000 metric tons of LiBs from EVs are expected to reach EOL by 2025 [7]. In Australia alone, due to the anticipated EV sales, it is estimated that 137,000 to 180,000 tonnes of LiB will come to the end of its life by 2036 [8]. However, as the demand for LiBs continues to grow so does the amount of waste generated at its EOL and coupled with current low collection and recycling rates, much of the LiB waste is lost in landfills [9]. The lost value estimated due to poor collection, offshore exports and poor recycling translates up to $3.1 billion in Australia [10].

At present, only three states in Australia (Victoria, South Australia and Australian Capital Territory) have banned e-waste disposal to landfills, with Western Australia due to introduce a ban in 2024 [11]. LiB waste has been termed as harmful and environmentally hazardous [8]. The most common electrolyte present within LiBs can cause respiratory failure, cardiac arrest and toxicity if handled incorrectly. Moreover, cobalt used for the production of EV LiBs is historically linked with human and environmental concerns [12].

As the demand for EV's and energy storage increases, so does the LiB waste [13, 14]. The typical life span of an EV LiB is estimated to be between 5 to 15 years [2]. This short life span highlights the need to mitigate concerns related to EOL EV LiB waste and capture the lost value due to EOL LiBs. Findings from CSIRO and ARUP estimate that a circular economy (CE) approach to the LiB industry could save around A$3 billion worth of materials leaving the Australian economy every year [15, 16]. A similar study focusing on the US has revealed savings of US $2 billion if 61% of EV's are reused in 2030 [10, 15]. To avail this opportunity, current businesses need to transition from a 'linear business model' to a 'circular business model (CBM)' creating a holistic network for new business opportunities for EOL EV LiBs in Australia.

The purpose of this study therefore, is to conduct an exploratory research to understand how EV based transport sector could be made more circular by focusing on EOL EV LiBs. The subsequent sections provide a literature review focusing on CE and CBM implementation for EOL EV LiBs followed by the status of developing a CBM in a context-specific environment. The literature review is followed by the research approach which outlines the methods of data collection and analysis. Section 4 presents and discusses the findings of this research. Conclusions and recommendations are drawn which are presented in section 5.

2. Literature review

2.1. *CE and CBM implementation*

The circular economy (CE) initiative is based on 3 design principles – maximizing the application of a product at their highest value, regeneration of natural systems and minimizing waste and pollution [17]. The concept of CE has been of interest to many researchers and industries [1] and it is often confused with recycling [18, 19]. However when considering maximizing the application of a product at their highest value and increasing resource efficiency, recycling might be the least sustainable outcome for a product [19]. The concept of a circular business model (CBM) can be defined as a business model (BM) to operationalise CE so that it provides economic, environmental, and social value to all stakeholders [3, 20] and acts as a regenerative tool for developing a holistic system based on CE principles [21].

The integration of CE into BMs is dependent on decision makers' strategies and ambitions. Most BMs are formed with a perspective of a single product life cycle [3] however, a CBM is implemented through collaboration and co-ordination of inter-dependent/multiple stakeholders from multiple perspectives [15, 22] including stakeholders involved in the value chain. The design of a CBM also introduces new variables from an environmental and social aspect that must be considered from a systematic and dynamic approach. However, a major finding revealed that current CBM tools lack the dynamic approach to address the on-going activities of an organization in response to its capabilities to internal and external changes [23]. This can also be justified through the findings of Hina et al. [24] and Schulz-Mönninghoff and Evans [25] wherein evidence suggests that despite the benefits of CBM, implementation has been slow especially in the manufacturing industry and that organizations lack the element of social inclusion and collaboration in the built environment context.

2.2. *Context based CBM implementation.*

Hina et al. [24] 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. A related study by Gajanayake et al. [26] on the drivers for businesses to adopt sustainability actions in Victoria, Australia concluded that while businesses want to 'do the right thing', it is dependent on the financial viability of the chosen strategy. Contrary to the drivers, the major barriers to introducing CBMs in organizations include lack of clear arguments for business and customer engagement, gap in role and relevance of CBMs and the lack of social and environmental considerations [25, 27, 28].

Research has shown that these drivers and barriers can be context specific [29] and hence, business models which prove to be effective for one sector may not succeed for another [24, 30]. Consequently, CBMs are also found to be context specific and must be developed and analysed in a specific manner [27]. A prominent example could include the findings of Ranta et al. [19], who found that recycling was seen as the most economically feasible outcome in the e-waste (information technology) industry, while in the context of EV LiBs, recycling is seen as a costly process [25]. Additionally, the overall consensus dictates that EV LiBs need to be repurposed before being recycled which is considered economical and environmentally sustainable [2, 21, 22, 31].

2.3. *CE for EOL EV LiBs*

In Australia, the EV sales nearly doubled from 2% of new car sales in 2021 to 3.8% in 2022 [32]. Hence, the focus of LiB waste from EVs is a growing concern, mainly due to the presence of lithium, nickel, manganese, and cobalt which are toxic materials, and which pose a threat to the environment and to human health [33, 34]. The CE approach can be used as a solution to mitigate this concern as it requires less materials to be used and consequently less waste being generated. Implementing CE requires organizations to transition from a 'take-make-throw' rationale to a circular approach, where stakeholders can gain maximum value at EOL.

Research on CE has mostly been generalized, however, research by Tura, Hanski [30] concluded that CE concepts are unique and context-specific and this may be applicable for the barriers and enablers for CE as well. Building on this finding, literature on the CE for EV lithium batteries revolve around reuse, repurpose in energy storage systems (ESSs), recycling to recover materials and refurbishment to repair EV batteries [31, 35]. Alternatively, these classifications can also be based on the 4R strategies (repair, remanufacture, repurpose and refurbish) as stated by many authors [36, 37]. However, it is important to address the many nuances found in the literature by representing CE based on the 10R strategy essential to consider the social and environmental aspect of developing a CBM for EOL EV LiB. These are represented based on the order of preference [38] as listed in Table 1.

Table 1. The relevance of R strategies to LiBs.

R strategy	Description/Explanation	Reference
Refuse	Prevention of the use of raw materials to produce EV batteries.	[38]
Reduce	Reduction in the reliance of raw materials to produce EV batteries.	[39]
Renew	Redesigning LiBs so that they are entirely circular.	[1]
Re-use	LiB at EOL being used for the same application i.e., EVs.	[40]
Repair	Faulty modules within batteries are replaced to enable the residual capacity of other modules which could be used for alternative application.	[34, 41, 42]
Refurbish	Repair and refurbishment of EV LiBs are often used interchangeably and no clear distinction exists.	[34, 41, 42]
Remanufacture	A combination of repair and reuse in which faulty or depleted modules are replaced to use the residual capacity and manufacture it to be similar to its original specifications.	[40]
Re-purpose	Use of EV LiBs for an alternate application such as a battery energy storage system.	[40]
Recycle	The process where EOL batteries are further mined to reclaim valuable materials which then serves as a feedstock to manufacture new products or materials.	[1]
Recover	The process involving the recovery of energy by incinerating LiB waste and materials which may be generated during recycling, remanufacturing, repair, repurpose or reuse.	[38]

2.4. *Developing a CBM for EOL EV LiB*

CBMs can be classified using multiple criteria but are often based on slowing or closing resource loops [29]. In the context of EV LiBs, Olsson et al. [37] classifies CBMs based on 4 possible scenarios as seen in Figure 1. These include a linear model representing the present scenario for EV batteries which is application in EVs followed by recycling. Optimized recycling refers to increased collaboration between the manufacturers and recyclers wherein recycling processes are automated and efficient to include multiple chemistries and complex designs. Circular model I refers to application in EVs followed by repair or refurbishment for reuse in EVs followed by recycling. Circular model II refers to application in EVs followed by repair or refurbishment for repurpose in a stationary energy storage system followed by recycling.

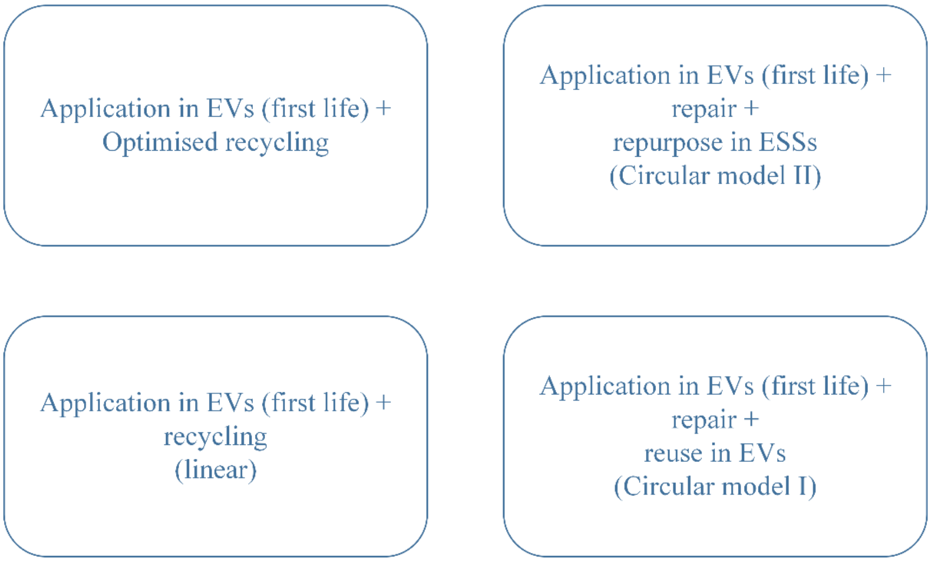

Figure 1. Classification of CBMs for EV LiBs adapted from Olsson et al. [37].

Depending on the barriers and enablers to each institution, certain business activities in these 4 scenarios are easier than others [43]. Galvão et al. [44] pointed that CBM research still consists of many challenges due to different perspectives from an intricate network of stakeholders on CE strategies and considerations [45]. Hence, the development of a CBM can be viewed as complex, dynamic and emerging [7]. A related study by Asgari and Asgari [46] concluded that for a smooth transition to CE, several BMs within a specific context must be balanced. However, research on CBM's for EV LiB are scarce and either focus on recycling or second use application [20, 22]. Moreover, much of the literature is dominated by CBM research conducted in the EU and Asia [47] and is still regarded as theoretical and conceptual based [48].

Collectively, these studies outline a critical role for developing a CBM considering different stakeholder perspectives and context-specific key factors. Hence, we address the lack of research on the development of CBMs to achieve circularity for EOL EV LiBs in Australia by conducting an exploratory study. As such, we aim to propose key strategic interventions to address growing concern of LiB waste emerging from EVs resulting in landfills.

3. Method

3.1. *Data Collection*

Given the exploratory nature of the research, semi-structured interviews were used as the primary source of data collection. The semi-structured interviews follow an interview protocol adopted and modified from [3] and [10] intended for stakeholder representatives from 5 groups: 1) EV manufacturers, 2) recyclers/repurpose/remanufacturers, 3) researchers, 4) not-for-profit/others and 5) government which have been identified and categorized based on the literature review. The participants were de-identified using codes to maintain confidentiality as seen in Appendix A.

Participants were selected based on their level of affiliation with the EV industry and experience dealing with EOL LiBs. Initially, participants were identified through the literature review and professional networking platform i.e., LinkedIn. Thereafter, snowball sampling approach was used to identify peer recommended relevant participants. Three pilot interviews were undertaken to assess duration of interview, clarity, order, and approach. The main feedback received was to assess the interchangeability of words used such as 'challenge' and 'uncertainty', shorten the interview questions and improve clarity of the questions.

3.2. *Data analysis*
This research adopted a combination of content and thematic analysis. The content analysis was used to categorize codes and identify the existence and frequency of words, characters, and relationships [49]. The thematic analysis was then used to facilitate the emergence of themes or patterns arising within the established codes. The selection of this approach was based on the methods adopted by Reinhardt et al. [45], Chirumalla et al. [22] and Olsson et al. [37]. A computer aided software NVivo was used to facilitate the data analysis which is complemented by the literature review. The resultant themes or patterns are used to identify new findings related to identifying key factors influencing the transition to circularity for EOL EV LiBs in Australia. To maintain confidentiality and ethical considerations, the participants were de-identified using codes as seen in Appendix A.

4. Results and Discussion

4.1. *Barriers and drivers to achieve circularity for EOL EV LiB in Australia*
Barriers are defined as the factors that hamper the implementation of CE for EV LiBs [50]. In addition to the lack of volume of EV LiBs at EOL, this study found regulatory barriers to be recurring among participants. Particularly, in the Australian context participants referred to the lack of homogeneity in the state policies contributing to barriers such as difficulty in transporting LiBs and the lack of collaboration. In response to the involvement of the government stakeholders in implementing CE for EV LiBs, participant M1 stated: *"So, the government has a very significant role to play, but not just in terms of this whole ecosystem, but also having a national approach as opposed to state-based approaches, which is what we've got at the moment".*

In contrast to the barriers, it was observed that all participants agree that government intervention in promoting standardization of batteries and increasing the uptake of EVs would be a major driver. Furthermore, the increase in government intervention was found directly proportional to increase in collaboration among relevant stakeholders. In response to the importance of collaboration and involvement of the government, participant G 3 responded: *"Uh, it's [collaboration] fundamental…. all levels of government and industry and the community in large have to collaborate. You know, it's a generic product stewardship model of shared responsibility."*

The existence of these drivers and barriers have contributed to the increase in dependence on the EU and other nations to which participant M1 responded: *"I think in Europe, they're well and truly advanced. This is sort of a non-issue over there. It's just Australia. Australia's got a long way to go to catch up".*

Considering that EV batteries need to be repurposed before being recycled which is considered sustainable, economic, and environmental, our exploratory study revealed that repurposing of EV batteries in Australia faces a greater challenge than recycling. This is primarily due to the present rate of uptake of EVs in Australia. A surprising response to this argument was provided by participant M3: *"I don't see it (repurposing) as being a future revenue stream or anything like that in the future. I'm not suggesting we're going to have a huge commercial roll out of second life batteries because we need to have a huge rollout of first life cars".*

Hence, referring to Figure 1, while Circular model II yields a higher value proposition, our exploratory study found that it would not be a suitable CBM option for EOL EV LiB in Australia. Alternatively, considering the present number of EVs in Australia and with the aim to prevent EOL EV LiBs from reaching landfills, we found that Circular model I may be a more suitable scenario. This finding was consistent with findings from that of Wrålsen et al. [51] who concluded that the most suitable CBM option includes "remanufacture + reuse + recycle + waste management". Although evidence of similar findings was not readily found in the literature, the exploratory study was useful to suggest the most likely solution to avoid disposal of EV LiBs in landfill in the built environment context.

4.2. *CE for EV LiBs from the stakeholder's perspective*

Considering the built environment context, participants were also asked to state what CE entails for EV LiBs. The analysis was useful to understand the ideology of CE for EOL EV LiBs from the stakeholder's perspective and the prioritization of recycling over repurposing in Australia. Interestingly, in addition to the 4Rs of CE (remanufacture, reuse, repurpose and recycle) [22], participants highlighted the importance of 'reduce' implying a reduction in overall processes associated with EOL management. Participant RRR 2, in response to highlighting the importance of CE stated: *"I think the only thing that's missing in the circular economy is reduce. We want it (CE for EV LiB) to be more efficient. So, you're not creating more stuff just to then repurpose it."*

Although participants are willing to engage in CE initiatives for EOL EV LiBs, the majority agree that a holistic approach and commitment are key to ensure a sustainable CE approach. As such, manufacturer M1 stated: *"When it comes to circular economy, it's how to land, the concept and the idea first and foremost. But then how to turn it into actions and that's really tricky. It comes down to hearts, minds, willpower."*

Additionally, participant RRR 1 stated: *"I think it comes back down to what we've been talking quite openly and during this whole interview process. It's about the directional leadership, approach and framework and coming from a holistic perspective."*

Hence, the commitment of stakeholders and a systemic approach dictate the success of the chosen CE strategy. The relevance of this implication was highlighted by [52] where a circular thinking guided by a systemic approach is essential to factor the context-specific impact of developing a CBM. Furthermore, the commitment of stakeholders is influenced by the introduction of financial incentives through government policies being a major driver. In relation to financial incentives, participant RRR 1 stated: *"I think every organization has their own approach to ESG sustainability and circular economy right because one of the key points with all these great topics and very important topics is about how does it affect commercially? What is my return on investment, my return on asset, my return on equity? Why would I want to spend time, money [and] effort on making something sustainable or circular….?"*

Additionally, in the context of CE, despite 'reuse' or 'repurpose' of EOL EV LiB being preferred over 'recycling', it is primarily dependent on a screening process based on the health of each battery cell [53]. However, participant RRR 2, engaging in 'repurpose' operations stated *"There are actually a good flow battery happening, but they're state of health is like 50% or less so…..and because they've been well used past what was expected that doesn't fit into our manufacturing process well"*

Hence, the preference of Circular model I is justifiable under the present market conditions in Australia. A similar study supporting this finding can be found in the conclusion derived from [54] where recycling in the US was found economical in the near term. Considering the built environment context, the driving factor to achieve circularity is therefore to opt for Circular model I until considerable amount of EV LiBs reach EOL. Thereafter, transitioning to Circular model II allowing stakeholders to develop collection and transportation infrastructures suitable to accommodate reprocessing activities.

Another implication in giving preference to Circular model I, is the societal and environmental benefits through the use and reuse of EV LiBs. On that note, participants were asked to state the benefits of CE for EOL EV LiBs. Overall, it was observed that CE in Australia is positively viewed among the stakeholder perspectives. Discussing the advantages of pursuing CE for EVs and EV LiBs, participant G5 stated: *"We're obviously trying to reduce those emissions to align to our enterprise-wide targets, but also obviously just trying to mitigate our impact on the environment as well."*

Additionally, on discussing the importance of CE for EV LiBs, participant NFP/O 3 stated: *"One of them is the most obvious one is that lithium batteries are toxic and we cannot really sit in the environment. We cannot landfill them and incineration of them is problematic also because of the toxic conditions coming out of the incinerators. So it's very important to manage this waste in an appropriate way"*

Hence, from a built environment context, CE for EVs and EV LiBs could result in a reduction of overall emissions compared to that from conventional vehicles. Furthermore, the use and reuse of EV LiBs could minimize the impact on environments and human health. Along the same lines, Masłowski, Kulińska [5] found that in narrow urban spaces, city buses emit greater amount of emissions if compared with EVs. Hence the preference of Circular model I could also infer that larger EV LiBs used in buses reduces carbon emissions thereby contributing to overall net zero targets of major city. Thereafter, by engaging in Circular model II, emissions emitted in the production of new EV LiBs can also be minimized by repurposing EV LiBs for an alternative application.

5. Conclusion and Recommendations

The aim of this research was to understand how EV based transport sector could be made more circular by focusing on EOL EV LiBs. An exploratory study using semi-structured interviews as a method of data collection was used. A thematic analysis of the interview data revealed that Australia is heavily influenced by the policy settings adopted by the EU and other nations. Moreover, the volume of the EOL EV LiBs is a major factor hampering the transition to CE for stakeholders in Australia. However, contrary to the consensus of repurposing and recycling EV LiBs respectively from the literature, this study found that repurposing in Australia faces a greater challenge than recycling. We propose adopting a CBM which focuses on repair or refurbishment of LiBs for reuse in EVs followed by recycling, which is similar to Circular model I proposed by Olsson et al. [37].

Such a model would be more suitable for immediate adoption within the Australian context and will minimize the disposal of LiBs in landfills. From a built environment context, this would minimize the threat of exposure of hazardous materials to human health and the environment and set the foundations for planning and zoning considerations across various jurisdictions. These considerations include setting up charging infrastructure for current EVs. Additionally, collection and transportation infrastructure required for the safe and efficient management of EOL EV LiBs. As such, sustainable urban planning is implemented which could benefit sectors that heavily rely on road transportation contributing to their environment, sustainability, and governance goals. On a broader scale, the repair and reuse of EV LiBs postpones the production of newer EV LiBs. As a result, the adverse effects on the environment and human health associated with cobalt [12] is mitigated. Moreover, this could also allow manufacturers to consider producing EV LiBs with fewer critical materials such as cobalt, nickel and manganese. On a societal level, the use and reuse of EV LiBs can also be associated with improving air quality for city dwellers [5]. Hence, we can argue that CBMs such as circular model I and II directly and indirectly contributes to mitigating climate change and achieving circularity for EOL EV LiBs.

This research is not without its limitations. This study focused on understanding factors influencing stakeholders from the EV LiB value chain to identify the most optimal CBM to achieve circularity. Hence, further research may consider expanding the range of participants from the EV manufacturer group and recycle-reuse-repurpose group. A key factor to be considered is the influence of government interventions on factors that hamper or mitigate the development of CBMs in context-specific environments; similar to the case of the EU where regulatory interventions work in sync with industry practices. Hence, we recommend further investigating the influence of government interventions on other business scenarios such as product-as-a-service models.

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Appendix A. Interviewed participants selected for the exploratory study.

Group	Code	Affiliation
Manufacturer	M 1	EV manufacturer
Manufacturer	M 2	EV manufacturer
	M 3	EV manufacturer
Recycle – Repurpose – Remanufacturer	RRR 1	EV battery remanufacturing, repurpose and recycle
Recycle – Repurpose – Remanufacturer	RRR 2	EV battery repurpose and recycle
Government	G 1	Victorian government
	G 2	Victorian government
Government	G 3	Victorian government
Government	G 4	Victorian government
Government	G 5	New South Wales government
	G 6	New South Wales government
Not-for-profit/other	NFP1	Not-for-profit organisation
Not-for-profit/other	NFP 2	Battery manufacturing industry
Not-for-profit/other	NFP 3	Not-for-profit organisation
Not-for-profit/other	NFP 4	Battery advisory organisation
Not-for-profit/other	NFP 5	Government affiliated body
Not-for-profit/other	NFP 6	Battery advisory organisation
Not-for-profit/other	NFP 7	Battery consultant
Researcher	R 1	University
Researcher	R 2	University
Researcher	R 3	Research organisation (battery related)
Researcher	R 4	Research organisation (battery related)