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Electric Vehicle Battery Remanufacturing: Circular Economy Leadership and Workforce Development

Bianca Ifeoma Chigbu *, Fhulu H. Nekhwevha and Ikechukwu Umejesi

Department of Sociology, University of Fort Hare, Alice 5700, South Africa; fnekhwevha@ufh.ac.za (F.H.N.); iumejesi@ufh.ac.za (I.U.)
* Correspondence: bchigbu@ufh.ac.za

Abstract: Given the increasing momentum globally towards sustainable transportation, the remanufacturing of used electric vehicle lithium-ion batteries (EV LIBs) emerges as a critical opportunity to promote the principles of the circular economy. Existing research highlights the significance of remanufacturing in resource conservation and waste reduction. Nevertheless, detailed insights into South Africa's (SA's) specific capabilities and strategic approaches in the context of used EV LIBs remain sparse. By utilizing in-depth interviews with fifteen key industry stakeholders and drawing on institutional theory, this qualitative study evaluates SA's infrastructure, technical expertise, and regulatory frameworks in the EV LIB remanufacturing sector to address this gap. The findings reveal proactive strategies, including technical expertise, sustainable infrastructure, and robust regulatory frameworks aligned with global standards. This study proposes strategic initiatives like the Interdisciplinary Innovation Hub and Mobile Remanufacturing Labs, which are analytically derived from stakeholder insights and aim to predict potential pathways for workforce development, especially in rural areas. Innovative training programs, including the Virtual Reality Consortium, Circular Economy Institutes, and the Real-world Challenges Program, will ensure a skilled workforce committed to sustainability and circular economy principles. The conclusions highlight SA's potential to become a leader in EV LIB remanufacturing by integrating circular economy principles, enhancing technical expertise, and fostering international collaboration.

Keywords: remanufacturing; electric vehicle lithium-ion batteries; circular economy; workforce development; sustainable innovation

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1. Introduction

As environmental consciousness and accelerated technological advancement coexist in the twenty-first century, remanufacturing electric vehicle lithium-ion batteries (EV LIBs) becomes essential for sustainable development. Remanufacturing batteries is one of the most critical sustainable alternatives as the world's adoption of EVs picks up speed. Recent developments in EV LIB remanufacturing include minimizing environmental effects, increasing battery life, and using less raw materials, establishing remanufacturing as a critical circular economy tactic [1,2]. The significance of used EV LIB remanufacturing can be better comprehended within the framework of the circular economy, which prioritizes resource efficiency, waste minimization, and the extension of product lifecycles [1–3]. Adopting circular economy principles in the remanufacturing process addresses climate change and promotes cleaner energy alternatives [4,5]. South Africa (SA) is positioned favorably in this sustainable transition due to the rapid growth of its EV industry [6].

While international recycling literature is abundant [7,8], SA's situation is unclear. Unlike countries like the United States or Germany, which possess extensive infrastructure and established rules that facilitate remanufacturing, SA faces constraints such as restricted technological capability and a developing regulatory framework. Nonetheless, SA's expanding EV sector and emphasis on worker development present considerable prospects for future expansion. Ref. [9] provide a foundation but lack the specificity to lead South African policies and initiatives. The shortage of an exhaustive assessment of SA's remanufacturing capacities emphasizes the need to thoroughly investigate the technological, infrastructural, and regulatory aspects that influence this sector. A critical factor in used EV LIB remanufacturing in SA is enhancing skills, including training and education development. A workforce with specialized training is imperative to navigate the intricacies associated with battery technology, material recovery, and sustainable practices [10]. This research examines the convergence of skill development and remanufacturing, focusing on educational initiatives and innovative training programs that cultivate a proficient workforce.

By extending the life of LIBs, reducing the demand for raw materials, and mitigating environmental impact via recycling [11,12], the remanufacturing process aligns with these principles. This research aims to comprehend the implications for sustainable development of integrating circular economy principles into remanufacturing used EV LIBs. Regulatory frameworks influence the EV LIB remanufacturing ecosystem in SA. To improve the remanufacturing process and ensure it adheres to sustainability objectives, it is imperative to examine current policies, potential challenges, and the impact of regulations on industry practices. Examining the challenges and opportunities presented by current policies, this study analyzes the regulatory environment regulating EV LIB remanufacturing in SA, considering developments in battery technology, obstacles encountered during material recovery, and procedural innovations [13,14]. Ref. [15] contend that social and policy innovations are necessary to tackle the obstacles associated with sustainable energy transitions. While significant research has been conducted on EV LIB remanufacturing in developed nations, such as Germany and China, the literature concerning developing countries—especially in Africa—is limited. This study offers an understanding of the EV LIB remanufacturing industry in SA by addressing the voids in the existing literature. This study addresses the literature vacuum by providing a detailed, contextual, analytical evaluation of SA's potential to develop the EV LIB remanufacturing sector, predicting potential growth pathways based on evaluating technical infrastructure, regulatory frameworks, and workforce capabilities. Specifically, it addresses the following key questions: (1) What are SA's current capabilities in EV battery remanufacturing? (2) How can circular economy principles be integrated into remanufacturing? (3) What regulatory challenges and opportunities exist in supporting this industry? (4) What strategies can be employed to reskill the workforce for sustainable practices? This research enhances understanding of sustainable development and EV LIB remanufacturing by analyzing technological, infrastructural, regulatory, and skill development components. The primary objectives are to evaluate SA's remanufacturing capabilities, investigate the integration of circular economy principles, analyze the regulatory landscape, and identify skill development and workforce reskilling strategies. This analysis aims to establish SA as a leader in the global initiative to establish a more sustainable and circular future in the EV industry. The organization of the subsequent sections is as follows: The literature on the circular economy, workforce reskilling, institutional theory, and lithium-ion batteries is the focus of Section 1. Section 2 illustrates the investigation methodology. Section 3 delineates this study's findings, encompassing global insights, innovative workforce reskilling pathways, and remanufacturing competence. The implications of the findings for theory and practice, as well as policy, industry, and educational recommendations, are the subject of Section 4. Section 5 concludes the primary discoveries and suggests avenues for additional research.

1.1. Literature Review

1.1.1. Background on Lithium-Ion Batteries

LIBs in EVs are crucial for the shift towards eco-friendly transportation because of their longevity, high energy density, and capacity to accommodate longer driving ranges. EV LIBs are explicitly made to satisfy the needs of high-performance electric cars, in contrast to LIBs utilized in other industries like consumer electronics or stationary energy storage [13,16]. The need for these batteries is rising as EV use increases globally, necessitating sustainable end-of-life management strategies, including remanufacturing [12,17]. Because of an EV LIB's adverse environmental effects, such as waste production and raw material depletion, remanufacturing is a crucial tactic. Remanufacturing old batteries can increase their useful life, recover valuable materials, and lessen their adverse environmental effects [18]. This approach promotes resource efficiency and adheres to the circular economy's tenets by encouraging reuse and reducing waste.

1.1.2. Workforce Reskilling and the Future of Work

The expanding EV battery remanufacturing industry presents distinctive challenges that necessitate a workforce with specialized technical expertise. That workforce must be highly trained. Reskilling programs are essential for providing employees with the requisite skills to perform tasks necessary for remanufacturing [10,19,20], including battery disassembly, refurbishment, and reassembly. EV battery remanufacturing necessitates a comprehensive comprehension of environmental sustainability and proficiency in safety protocols. This is in contrast to traditional manufacturing. It is imperative to forge strategic partnerships among academic institutions, regulatory bodies, and industry stakeholders to address skill deficits. This will guarantee that training programs incorporate both theoretical and practical applications. These initiatives will satisfy the sector's specific skill requirements and aid in realizing Sustainable Development Goal 8 (SDG 8), encouraging economic growth and decent work [21,22].

1.1.3. Infrastructure and Circular Economy

The successful integration of circular economy principles into EV battery remanufacturing heavily depends on robust infrastructure [23]. This comprises sustainability metrics to guarantee the longevity and efficacy of remanufactured batteries, advanced information technology systems for battery monitoring, and state-of-the-art logistics for efficient material recovery. Infrastructure development in the electric vehicle sector necessitates meticulous control to prevent rebound effects, resulting in increased resource consumption due to improved efficiency [24]. Well-designed infrastructure is necessary to mitigate environmental impacts and facilitate the scalability of EV battery remanufacturing during the transition from a linear to a circular system [25,26]. In addition, it is imperative to maintain an ongoing investment in research and development to meet the industry's changing technical requirements and to enhance the efficiency of remanufacturing processes [27,28].

1.1.4. Advances in Cooling Technology for EV LIBs

As the technology of EV batteries has continued to advance, thermal management systems have become essential in enhancing battery performance and extending the lifespan of the batteries. Phase change materials (PCMs) are among the most recent advancements in cooling systems, which assist in regulating battery temperatures by absorbing excessive heat during operation. Research indicates that these systems can significantly enhance battery life and overall performance by reducing temperatures by as much as 30% [29]. EV battery modules can regulate heat more efficiently by utilizing sophisticated composite PCMs, such as paraffin and high-porosity copper foam [30]. This, in turn, mitigates the risk of overheating, extends the battery's lifespan, and promotes the sustainability of remanufactured batteries. Although these technologies are primarily focused on improving the performance of new batteries, their integration into remanufacturing processes could further enhance the quality and durability of reused EV batteries [31–33].

1.1.5. Embracing Institutional Theory in the Evolution of EV LIB Remanufacturing

An analysis of the impact of the institutional environment on the remanufacturing of EV LIBs in SA can be conducted through the lens of institutional theory, which is based on sociology and organizational studies [34]. By extrapolating insights from the research conducted by [35] regarding the construction sector in the United Kingdom

(UK), it becomes possible to comprehend how variations in industry practices and inter-organizational dynamics influence skills development. The remanufacturing competency, facility capabilities, and workforce reskilling within the EV LIB remanufacturing sector are all influenced by the institutional context, which comprises government mandates, industry standards, and societal norms [36–39]. In this context, the capabilities of firms and their implementation of circular economy practices are substantially influenced by policies and regulations [40–42].

Coercive, mimetic, and normative isomorphism impact organizations, resulting in adopting practices that conform to institutional expectations and international standards [43,44]. Organizations may, for instance, adopt particular environmental practices or remanufacturing procedures to acquire credibility and acceptance in the industry and society. Furthermore, the reskilling of the EV LIB remanufacturing sector reflects the trends observed in the UK construction industry. Changing institutional norms and the imperative to bridge skill gaps frequently influence skill development initiatives [10]; organizations modify their workforce to align with evolving industry standards and sustainability responsibilities [45,46]. Figure 1 presents a conceptual framework illustrating the institutional influences on EV LIB remanufacturing.

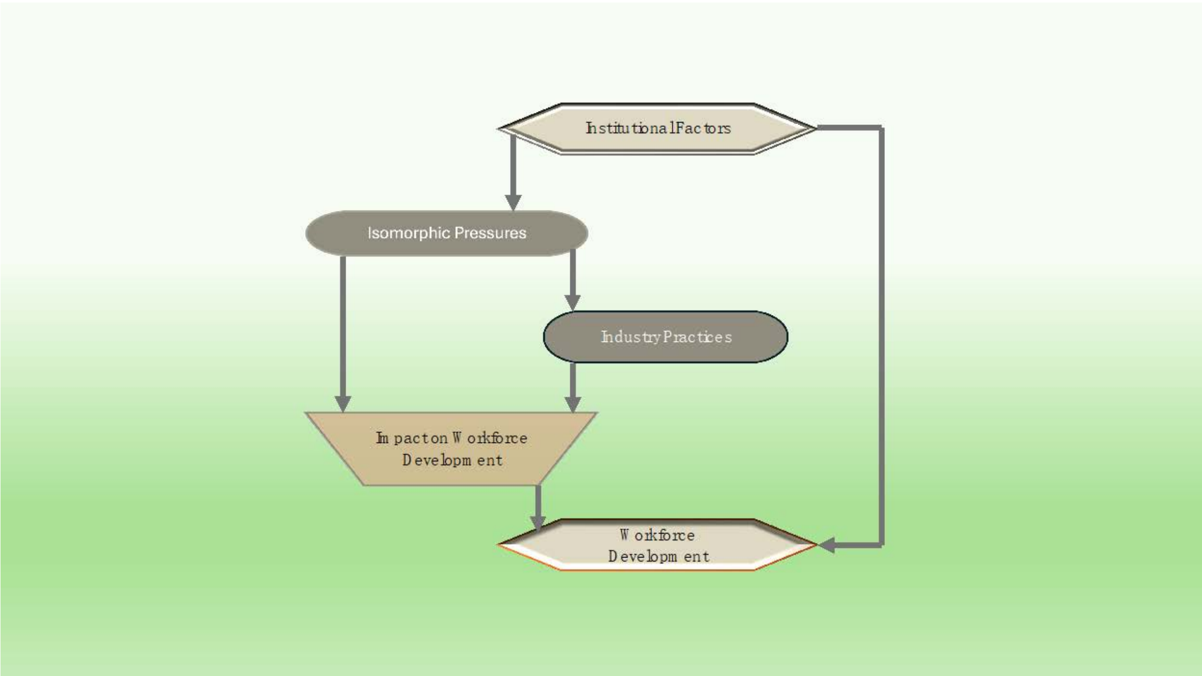

Figure 1. Institutional Influences on EV LIB Remanufacturing: A Conceptual Framework.

Thus, institutional theory offers a conceptual structure for comprehending the intricacies of the South African EV LIB remanufacturing sector. Through an analysis of how institutional factors impact remanufacturing practices, facility capabilities, and workforce development, valuable insights can be obtained regarding the obstacles and prospects in the sector's pursuit of sustainable development and the circular economy.

2. Materials and Methods

2.1. Research Methods

Globally, the demand for EVs is projected to grow at a compound annual growth rate of 21.7% from 2021 to 2030, with sales expected to reach 34 million units by 2030 [47]. While currently lagging in EV adoption, SA is expected to see significant growth due to governmental initiatives. The challenge of disposing of EV LIBs responsibly is increasingly pressing. This research investigates how SA can capitalize on this opportunity by establishing a sustainable EV LIB remanufacturing sector, which could reduce environmental impact and create economic opportunities. This study used a qualitative research approach, with in-depth interviews to elicit viewpoints from key stakeholders in SA's emerging EV LIB remanufacturing industry. The selection of the qualitative methodology was predicated on its appropriateness for investigating intricate, situation-specific phenomena, and capturing the subtle viewpoints of participants [48]. The principal method of obtaining information was in-depth interviews, which facilitated an extensive investigation into the participants' perspectives, insights, and experiences relating to the remanufacturing ecosystem. These interviews provided rich qualitative data on SA's intentions, plans, and progress in developing the necessary technological competency, infrastructure, and regulatory frameworks for long-term EV LIB remanufacturing. Using open-ended questions in interviews allows for participants to express their thoughts freely. For instance, "How would you characterize the current technical expertise, infrastructure, and regulatory frameworks in SA concerning the remanufacturing of used EV LIBs?" enables the participants to provide comprehensive and detailed responses.

2.2. Participants

Fifteen people were selected to represent critical viewpoints on the South African EV LIB remanufacturing ecosystem. Purposive sampling [49] was utilized to ensure the interviews included diverse perspectives from the EV LIB remanufacturing industry. The expertise prioritization was based on critical domains, including technical proficiency, regulatory aspects, and circular economy practices. Academic, government, business, non-governmental organizations, and industry sectors were represented among the participants to ensure a broad spectrum of perspectives. The selection process was also considered an influence, as applicants were chosen according to their substantial impact on SA's EV LIB remanufacturing industry. A consultant specializing in international remanufacturing offered global perspectives; an industry leader provided market insights and regulatory challenges; a workforce development specialist contributed knowledge on training needs and skills enhancement; and a proponent of the circular economy emphasized sustainability and circular principles. Collectively, these participants enhance the collective comprehension of the remanufacturing environment by addressing workforce, sustainability, regulatory, and global factors. The institution's ethics committee's approval guaranteed compliance with all ethical standards and regulations. All participants gave consent, and we ensured confidentiality and anonymity.

2.3. Materials and Preparation

This study included three face-to-face interviews for more personalized and in-depth stakeholder involvement. This method facilitates deeper discussions and rapport between researchers and participants [50]. Two Zoom interviews were also conducted to accommodate participants' busy schedules and locations. Zoom made the interview process more accessible and flexible, allowing for stakeholders from far away to contribute. Digital recording equipment was used for in-depth stakeholder interviews to capture insights accurately and verbatim. The interview questions were designed through a structured process that began with identifying the core research objectives and themes. The research team first identified critical areas related to the remuneration of end-of-life EV LIBs in SA, including technical expertise, infrastructure, regulatory frameworks, and workforce reskilling. Based on these areas, open-ended questions were developed to elicit rich, detailed responses directly addressing this study's research goals [51].

The development of the interview questions was also informed by the relevant literature on remanufacturing, circular economy principles, and workforce development. Prior studies on LIB remanufacturing, particularly in developed markets like the United States and Germany, provided a comparative basis for understanding the challenges and opportunities in SA. This approach ensured that the interview questions were tailored to gather insights specific to the South African context while grounded in established global trends and challenges.

Each interview question was carefully designed to correspond with a specific research objective, guaranteeing a focused investigation into SA's EV LIB remanufacturing ecosystem. The goal was to cover a comprehensive range of topics while maintaining clarity and alignment with the study aims. For example:

- "How would you characterize the current technical expertise, infrastructure, and regulatory frameworks in SA concerning remanufacturing end-of-life EV LIBs?" This question is closely aligned with the study's primary research objective: to evaluate SA's existing technical and infrastructural capabilities in the remanufacturing space. It was developed based on existing research highlighting infrastructure and regulation's critical role in successful remanufacturing operations [52]. The aim is to understand the country's readiness for large-scale remanufacturing initiatives and identify any gaps that must be addressed.
- "What strategic measures may SA use to reskill its workforce for the specific demands of remanufacturing EV LIBs?" This question corresponds with the fourth research objective: exploring workforce reskilling approaches. It was designed after reviewing the literature on the importance of workforce development in emerging industries, particularly in circular economy practices [10,53]. By framing the question this way, the research aimed to uncover practical, context-specific strategies for upskilling and retraining SA's labor force to meet the unique demands of EV LIB remanufacturing.
- "How can labor reskilling contribute to long-term EV LIB remanufacturing operations in the circular economy?" This question pertains to the second research objective, which examines integrating circular economy principles into remanufacturing. Drawing from previous studies that explore the intersection of sustainability and workforce education [18], this question seeks to gather insights into how reskilling initiatives can foster sustainable practices in remanufacturing and align with global trends in green technology adoption.

The research maintained a coherent and intentional trajectory throughout the data collection process by ensuring that each interview question was directly linked to this study's core objectives. This approach provided stakeholders with a structured yet flexible framework to provide detailed, context-specific insights into SA's evolving EV LIB remanufacturing ecosystem. Additionally, the open-ended nature of the questions allowed for participants to offer nuanced perspectives, enriching this study's findings with qualitative depth.

2.4. Data Analysis

The data for this study were analyzed using thematic analysis, a highly appropriate technique for analyzing the comprehensive and complex data gathered from the interviews [54,55]. By employing this methodology, it was possible to discern and investigate common themes that surfaced in the responses of the participants, all of whom offered insightful perspectives on the ecosystem of EV LIB remanufacturing in South Africa. The researchers conducted a comprehensive review of the transcribed interviews to engage with the data fully. The preliminary phase was of utmost importance in comprehending the extent of the participants' perceptions and determining initial developments. The participants' viewpoints were systematically categorized into codes, each corresponding to a distinct aspect. The research objectives were a guiding framework for this procedure, guaranteeing that the codes corresponded to the fundamental domains under investigation, including regulatory frameworks, circular economy practices, and technical proficiency. Following this, the codes were categorized into possible themes that embodied the fundamental understandings of the EV LIB remanufacturing ecosystem. The themes were reviewed and refined to ensure they accurately reflected the participants' perspectives and the research objectives, ensuring coherence and representativeness [22,56].

The themes need to be defined and named in a way that effectively communicates their essence [57,58], as this was what determined their significance and applicability to this study's primary goal regarding the EV LIB remanufacturing ecosystem. The results were disclosed by integrating the thematic analysis and participant quotations. The themes were deliberated in relation to the research objectives [55], and the analysis was substantiated by appropriate scholarly works to comprehend the remanufacturing ecosystem in SA thoroughly. By adopting this methodology, an organized and transparent examination was conducted, thereby strengthening the trustworthiness and validity of the results. To provide a clearer view of the data, Table 1 below summarizes the key interview questions, the number of responses for each, and the main themes that emerged from the analysis.

Table 1. Summary of interview questions, responses, and key themes from thematic analysis.

Interview Question	Number of Responses	Key Themes and Insights
How would you characterize the current technical expertise, infrastructure, and regulatory frameworks in SA concerning remanufacturing end-of-life EV LIBs?	5	Gaps in technical expertise; inadequate infrastructure; regulatory challenges and the need for reform
What strategic measures may SA use to reskill its workforce for the specific demands of remanufacturing EV LIBs?	4	Workforce reskilling initiatives; collaboration between industry and academia; vocational training programs
How can labor reskilling contribute to long-term EV LIB remanufacturing operations in the circular economy?	3	Integration of circular economy principles; sustainability and green technologies; long-term workforce development
From a regulatory standpoint, what initiatives or standards are in place to ensure advanced remanufacturing of EV LIBs, and how do they compare globally?	3	Lack of comprehensive regulatory frameworks; global benchmarking; safety and environmental standards

This table summarizes the major interview questions used in this study, the number of responses, and the main themes that emerged during the analysis. Each interview was coded based on how participants addressed specific areas of technical expertise, workforce development, and regulatory frameworks aligned with the study objectives.

2.5. Limitations

While the data are comprehensive, the small sample size may limit generalizability. This study's focus on individual stakeholders may neglect the viewpoints of other key EV LIB remanufacturing ecosystem actors. More industry and participant perspectives are needed in future investigations. Ethical considerations and transparency in reporting boost this study's credibility and replicability, making its findings robust and valuable for subsequent research and policy choices.

3. Results

SA's ground-breaking remanufacturing business for EV LIBs is described in this section. Using insightful conversations with participants, we examine the country's goals, strategies, and progress in establishing the critical technological proficiency, cutting-edge infrastructure, and progressive regulatory frameworks needed to demonstrate a sustainable EV LIB remanufacturing environment.

3.1. Evaluating Remanufacturing Competence

We examine the country's emerging strategies and position concerning developing critical technological proficiency, cutting-edge infrastructure, and progressive regulatory frameworks. Based on interviews with prominent industry stakeholders, this section provides an overview of the innovative remanufacturing business for EV LIBs in SA. Interviews were conducted between 2023 and early 2024, with participants representing a variety of sectors, including academia, industry, and government. These interviews were conducted in person at critical industry locations and virtually through online platforms such as Zoom, guaranteeing diverse viewpoints. These stakeholders are representatives of the South African EV LIB remanufacturing industry's broader ecosystem, as they are directly involved in workforce education initiatives, technological development, and policymaking. The interviews offer a comprehensive perspective on SA's preparedness for EV LIB remanufacturing by interacting with key policy, education, and hands-on industry work stakeholders. Consequently, these participants' perspectives indicate the country's overall approach to this emerging industry.

3.1.1. Pioneering Sustainable Mobility

This section delves into SA's strategic initiatives and developing plans to establish a remanufacturing industry for used EV LIBs. A government regulatory expert was asked two questions: (1) How would you characterize SA's current technical expertise, infrastructure, and regulatory frameworks concerning remanufacturing used EV LIBs? (2) From a regulatory standpoint, what initiatives or standards are in place to ensure the advanced remanufacturing of EV LIBs, and how do they compare globally? This expert provided a comprehensive overview, outlining initial steps in developing technical expertise, advanced infrastructure, and forward-thinking regulatory frameworks. Through proactive measures and international benchmarking, SA aspires to foster a sustainable and globally competitive landscape for EV LIB remanufacturing. The expert's verbatim response provides insight into the anticipated developments in the remanufacturing sector:

> *"Presently, SA is at the nascent phase of establishing the regulatory frameworks, technical skills, and infrastructure required for the EV LIB remanufacturing business. Acknowledging the significance of a solid groundwork, a deliberate endeavor is made to foresee and attend to critical elements: There are current preparations to develop technical proficiency in the disassembly, refurbishment, and reassembly of EV LIBs. This entails forging partnerships with academic establishments and industry professionals to develop customized training programs precisely designed to address the expected demands of the remanufacturing sector. In anticipation of the expected need for facilities, preparations are underway to construct cutting-edge infrastructure outfitted with contemporary technology. Preventive measures are also implemented to develop regulatory frameworks overseeing the expected remanufacturing operations."*

The success of remanufacturing industries is contingent upon a robust technical infrastructure and a well-established regulatory framework, and the literature supports this notion [40,59]. The prioritization of safety and environmental sustainability is consistent with worldwide patterns observed in the remanufacturing and circular economy sectors [24]. Furthermore, the emphasis on cultivating technical proficiency via collaborative ventures and educational initiatives aligns with the remanufacturing industry's demand for skilled workers [43].

The expert's response sheds light on the critical areas of focus for the emerging remanufacturing sector:

> *"Future laws will address ecological problems associated with EV LIB remanufacturing, ensuring that the procedures are consistent with sustainable methods and have a minimal environmental impact."* This focus on lessening the ecological impact of battery manufacturing and disposal is consistent with international initiatives to incorporate environmental sustainability principles into remanufacturing processes [24].

> "*Plans are in place to set strict quality criteria for remanufactured EV LIBs. This will include testing and certification procedures to ensure that remanufactured batteries meet or exceed performance standards.*" Ensuring quality assurance is of the utmost importance in establishing consumer confidence and is consistent with global benchmarks for battery remanufacturing [60,61].

> "*Efforts are being developed to certify the future workforce to meet the demand for trained technicians. Specialized training programs are in the works to provide persons with the necessary expertise for EV LIB remanufacturing.*" The emphasis on the importance of workforce development aligns with the remanufacturing industry's demand for proficient people and reflects worldwide patterns in technical education and training [10,20].

The expert's statement on international benchmarking highlights SA's commitment to adopting global best practices in EV LIB remanufacturing. "*The continual benchmarking against worldwide standards assures that the developing industry follows responsible and competitive procedures.*" This approach ensures that SA's remanufacturing industry remains aligned with international norms and is competitive in the global market.

3.1.2. Unveiling South Africa's EV LIB Remanufacturing Landscape

Automobile companies in SA are spearheading advancements in technical expertise, infrastructure, and regulatory compliance within the burgeoning field of EV LIB remanufacturing. In this section, two questions were posed to an industry leader—an EV manufacturer representative: Can you provide insights into the technical expertise, infrastructure, and regulatory compliance associated with EV LIB remanufacturing within your company and the broader industry in SA? How do you perceive the global positioning of SA concerning facilities and capabilities for dismantling, refurbishing, and reassembling EV LIBs?

The industry leader prioritized strong technological knowledge, cutting-edge facilities, and strict regulatory compliance in the South African automotive industry. "*Our technical teams possess specialized knowledge and can dismantle, repair, and reassemble EV LIBs as needed to ensure that the remanufactured batteries meet high-performance criteria.*" The emphasis on technical proficiency is consistent with worldwide patterns in the remanufacturing industry, where technological progress is vital for guaranteeing quality and efficiency [60].

The industry leader acknowledged challenges and opportunities in the current state of EV LIBs in SA. "*While the electric vehicle industry is still expanding, there has been a considerable increase in interest and acceptance.*" Key emerging sub-themes of this section are the significance of public–private partnerships for fostering innovation, the contribution of research and development to enhancing technical proficiency, and the necessity of a supportive regulatory framework to guarantee environmental sustainability and safety standards [62].

3.2. Investigating Innovative Approaches to Workforce Reskilling

Embarking on exploring innovative pathways for workforce reskilling in EV LIB remanufacturing, this section delves into strategic measures and creative training programs designed to equip SA's labor force for the specific demands of sustainable practices. The research objective unfolds visionary responses proposing strategic approaches.

3.2.1. Innovative Pathways

The reskilling journey for EV LIB remanufacturing occurs through a dynamic combination of strategic planning, collaborative collaborations, and ground-breaking educational programs. We asked a workforce development specialist the following essential questions: What strategic measures may SA use to retrain its workforce for the specific demands of remanufacturing EV LIBs? Are there any creative training or educational programs that may be introduced to provide the workforce with the requisite knowledge and skills, hence building a sustainable environment for EV LIB remanufacturing practices? The following extracts reveal their visionary responses: The specialist proposed innovative strategies for workforce development: "*SA may establish Mobile Remanufacturing Labs, a partnership between leading EV manufacturers, mobile education providers, and vocational training organizations. These labs provide hands-on instruction to prospective technicians in rural areas.*" These laboratories can address accessibility challenges in remote locations and ensure that technical education is accessible to a broader population.

Another proposed strategy is the development of an "Interdisciplinary Innovation Hub", fostering collaboration between engineering institutions and environmental science departments. "*While engineering students focus on technical issues, environmental science students provide insights into sustainable practices, resulting in a more holistic learning environment.*" This interdisciplinary approach promotes a thorough comprehension of the technical and environmental facets of remanufacturing, as discussed by [43].

The specialist highlighted the need for creative training solutions: "One idea is the Virtual Reality Consortium, offering immersive VR experiences for EV LIB remanufacturing, allowing technicians-in-training to troubleshoot complex scenarios in a digitally simulated environment." Additionally, the establishment of "Circular Economy Institutes" across provinces can merge business schools with environmental studies departments. "These institutes can integrate business acumen with ecological consciousness by offering courses tailored for the EV LIB remanufacturing sector and its likes." This initiative promotes integrating circular economy principles into business practices and education.

The Real-world Challenges Program is another notable project that can foster industry–university collaboration: "An EV manufacturer interacts with a university's mechanical engineering department, allowing students to work on actual remanufacturing projects provided by the company." Such hands-on experience stimulates academic creativity and provides valuable practical skills [63–65]. An examination of the interview quotes identified critical themes in workforce development for EV LIB remanufacturing: the need for creative learning approaches, the significance of inter-sector cooperation, and the incorporation of sustainability principles in educational and training initiatives. The focus on enhancing the workforce through education and skills development is essential to bolster developing industries, including green technologies and remanufacturing sectors [66].

3.2.2. Circular Expertise Unleashed

Our circular economy advocate, shedding light on a road towards sustainable EV LIB remanufacturing, discusses the transforming significance of reskilling in preparing technicians to be stewards of circular ecosystems. Imagine a paradigm change through new training programs in which workers develop technical competency and internalize circular economy ideas. How can labor reskilling contribute to long-term EV LIB remanufacturing operations in the circular economy? How do new training programs help match the workforce with circular economy concepts in EV LIB remanufacturing? In this inquiry, the advocate envisions technicians as sustainability advocates, effortlessly integrating their knowledge with the principles of reduce, reuse, and recycle, ushering in a new age of ethical EV LIB remanufacturing.

The participant points out the role of reskilling in embedding sustainability into the remanufacturing process: "Reskilling the workforce is fundamental in advancing sustainable practices within the EV LIB remanufacturing domain. Technicians become the custodians of circularity, with a comprehensive understanding of each battery's lifecycle, ensuring responsible disposal and material reintegration." A technician imbued with circular economy principles is proficient in enhancing the longevity of EV LIBs through efficient refurbishment. Their expertise extends to identifying components for reuse, thereby reducing waste and epitomizing the "reduce, reuse, recycle" ethos. This methodology not only conforms to the principles of the circular economy but also fosters a feeling of accountability, transforming every EV LIB remanufacturing process technician into a sustainability advocate.

The interviewee highlights the pivotal role of training programs: "In the context of EV LIB remanufacturing, innovative training programs are essential for embedding circular economy concepts into the workforce. Envision a curriculum that melds cradle-to-cradle thinking with standard skill-building modules, enabling technicians to understand the environmental impact of their actions." Collaboration with sustainability experts can further enrich the learning experience. "Imagine a training session where environmental scientists work alongside technicians to brainstorm circular solutions. This collaborative learning enhances technical proficiency and nurtures a mindset where every action contributes to a circular and regenerative approach in EV LIB remanufacturing." Scholars such as [66,67] emphasize the need for skill development in green industries, particularly in remanufacturing. Key emerging sub-themes in this section are the significance of public–private partnerships in creating training programs, the use of technology to replicate real-world sustainability challenges, and the necessity of a multidisciplinary approach that integrates technical expertise with environmental consciousness.

3.2.3. Global Insights, Local Brilliance

We opened a discussion with our international remanufacturing consultant and learned more about the exciting world of EV LIB remanufacturing. In the conversation, the consultant presents a vision of practical apprenticeships and international partnerships, illustrating a future in which SA's labor force welcomes and thrives in the complex processes of EV LIB remanufacturing globally. Here are the questions asked and the responses below: Based on global best practices, what innovative approaches have been successful in workforce reskilling for EV LIB remanufacturing? How can SA collaborate internationally to integrate innovative training and educational programs for a skilled workforce in EV LIB remanufacturing?

The consultant emphasizes the significance of experiential learning in reskilling: "The key to effectively reskilling the workforce for EV LIB remanufacturing on a global scale is similar to an experiential apprenticeship where enthusiastic technicians get their hands dirty disassembling, restoring, and assembling EV LIBs alongside more seasoned specialists." International conferences are highlighted as platforms for knowledge exchange: "These are get-togethers when professionals worldwide exchange experiences and methods. Our technicians could learn extensively by attending to them and keeping up with developments. Bringing these international best practices home might be transformative, ensuring our workforce possesses exceptional and world-class EV LIB remanufacturing skills." The literature confirms the effectiveness of hands-on learning in technical domains, as the consultant advocates for experiential apprenticeships. Immersive, hands-on experiences significantly improve the acquisition of technical skills, aligning with the consultant's idea of technicians learning directly from experienced professionals. This supports the consultant's recommendation that these platforms can help raise SA's workforce to international levels.

The consultant outlines the potential for international collaboration: "South Africa can collaborate with other nations to strengthen our workforce for EV LIB remanufacturing, especially where EV is well established. We are discussing collaborative initiatives, our academics traveling for knowledge sharing, and developing a curriculum that is the best in the world and mingling with global industry elites." The importance of a comprehensive skillset is stressed: "Ensuring our workers have the whole toolkit is more important than simply checking boxes. By forming these international alliances, we hope to compete equally with other worldwide leaders in EV LIB remanufacturing."

This emphasis on experiential learning, knowledge exchange, and collaborative initiatives highlights the multi-faceted approach required to elevate SA's position in the global remanufacturing landscape. The consultant's vision for international cooperation aligns with [68] research, showing how worldwide educational collaborations have enhanced workforce capabilities in developing industries. This research supports establishing partnerships with prominent organizations in advanced EV markets to create training programs jointly. It suggests that these collaborative initiatives have the potential to position SA as a global leader in EV LIB remanufacturing. [69,70] advocate the idea of a worldwide digital club for interacting with industry leaders, highlighting the influence of digital platforms in overcoming geographical barriers to promote international learning communities. This aligns with the interviewee's view on utilizing worldwide knowledge through digital cooperation to provide South African workers with extensive training materials.

A visual summary of this study on the EV LIB remanufacturing industry in SA is presented in Figure 2.

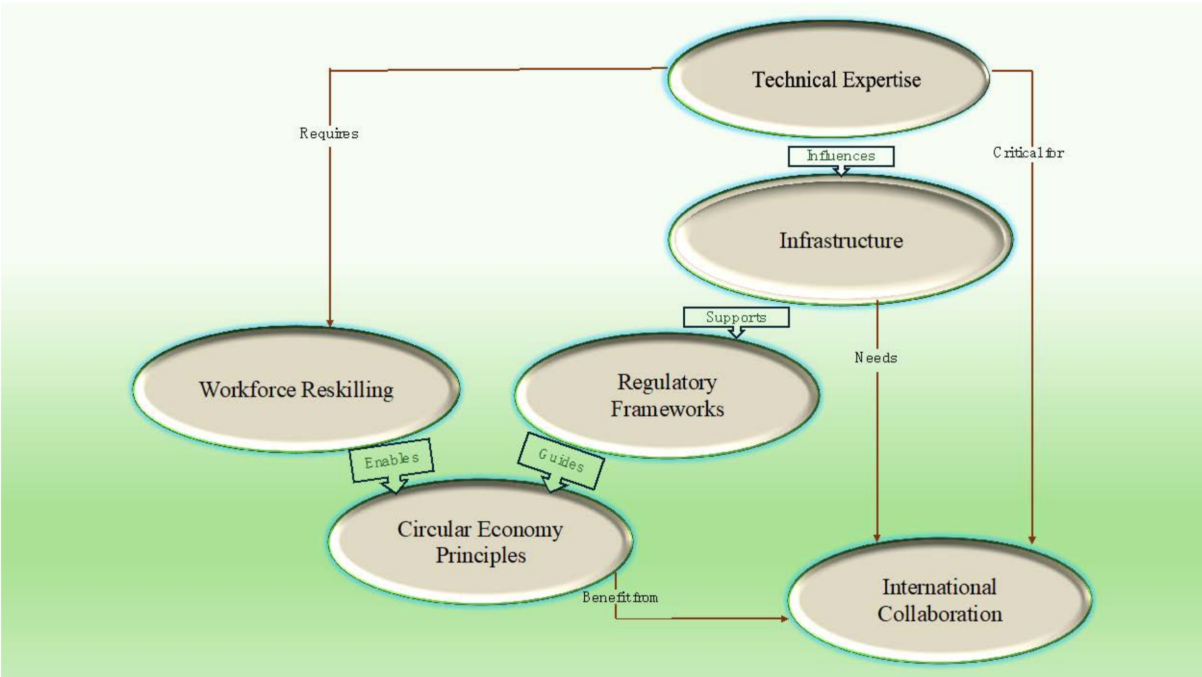

Figure 2. Key components of South Africa's EV LIB remanufacturing ecosystem.

The above figure highlights six essential elements that are critical for the establishment of a sustainable ecosystem for EV LIB remanufacturing:

1. Technical Expertise → Highlighting the importance of developing skills in disassembly, refurbishment, and reassembly of EV LIBs.
2. Infrastructure → Emphasizing the need for cutting-edge facilities equipped with modern technology to support remanufacturing processes.
3. Regulatory Frameworks → Underlining the establishment of regulations that prioritize environmental sustainability, safety measures, and quality standards.
4. Workforce Reskilling → Focusing on creating specialized training programs to equip workers with the necessary expertise for remanufacturing.
5. Circular Economy Principles → Stressing the integration of circular economy concepts to enhance resource efficiency and minimize waste.
6. International Collaboration → Pointing out the role of global benchmarking and partnerships in adopting best practices and ensuring competitive positioning in the worldwide market.

The figure encapsulates the interconnectedness of these components, illustrating how each contributes to the overall goal of fostering a sustainable and globally competitive landscape for EV LIB remanufacturing in SA.

4. Discussion

4.1. Remanufacturing Expertise

SA's proactive technology, infrastructure, and legislation approach meshes with worldwide sustainable mobility discussions. Refs. [71,72] agree that sustainable industrial practices require comprehensive methods integrating technical innovation, infrastructural development, and regulatory institutions. Joining forces with academic institutions and industry professionals is consistent with [19,37], who emphasize the importance of collaborative ecosystems in developing technical competence in growing sectors. SA's dedication to forecasting key remanufacturing industry factors reflects circular economy planning. Ref. [73] found that emerging enterprises must follow worldwide norms to be competitive. Environmental sustainability, quality control, and safety measures support [74] circular economy concepts, stressing responsible growth.

4.2. Reskilling of Labor Forces

Innovative worker reskilling methods mirror transformational learning and transdisciplinary education discussions. The "Mobile Remanufacturing Labs" and "Multidisciplinary Innovation Hub" promote interdisciplinary education and experiential learning [75]. The study shows that reskilling may promote sustainable behaviors, consistent with circular economy studies [66]. However, several studies warn against overusing technology-driven reskilling. These studies reflect concerns about demographic exclusion and emphasize the importance of inclusive and accessible services [76].

4.3. International Insights

This study highlights worldwide worker reskilling benchmarks. Experiential learning and collaborative platforms for information sharing match with scholarly research stressing worldwide cooperation in knowledge dissemination [77]. SA's goal of global leadership aligns with the importance of early adopters and leaders in sustainability transformations.

4.4. Implications for Practice and Theory on a Broader Scale

The findings highlight SA's EV LIB remanufacturing business's theoretical and practical relevance. The national commitment to sustainable mobility corresponds with theoretical frameworks integrating legal, infrastructural, and technical factors to improve industry. The educational environment is changing as collaborative learning spaces and new training programs emphasizing transdisciplinary and experiential approaches become more important [78,79]. This study helps policymakers, industry leaders, and researchers shape EV LIB remanufacturing. Innovative methods for reskilling and adapting the workforce may inspire industry leaders. Interdisciplinary and experiential learning may teach students technical skills and circular thinking [80,81]. The interview findings emphasize the role of proactive regulatory frameworks and the necessity for technical innovation in remanufacturing EV LIBs. This aligns with broader global trends of sustainable mobility practices. Moreover, to ensure the financial sustainability of remanufacturing, it is critical to consider the economic benefits it can offer. While this study's primary data are qualitative, the existing literature indicates that remanufacturing EV LIBs can lead to a 9.81% to 30.93% increase in profit, which can stimulate job creation and contribute to GDP growth by promoting economically sustainable supply chain management in the EV battery industry [82]. Remanufacturing LIBs significantly decreases production costs compared to manufacturing with virgin materials. For instance, the direct physical recycling (DPR) approach may cut production costs by 25.61% to 36.63% [8]. The potential cost-saving from battery remanufacturing is around USD 1.87 for every kilogram of cell produced, making it economically feasible until the purchase price of used batteries climbs to USD 2.87 per kg [83]. South African EV LIB remanufacturing meets high standards with practical and theoretical breakthroughs. It would support SDGs 8 and 12, the circular economy, decarbonization, employment, and just transition.

4.5. Recommendations

Based on the interviews conducted with key stakeholders, the following specific recommendations are proposed:

Participants consistently noted the absence of specialized technical expertise in the breakdown, refurbishment, and reassembly of EV LIBs. To resolve this issue, we recommend the establishment of formal partnerships between academic institutions and industry to create practical training programs that concentrate on remanufacturing electric vehicle batteries. This could involve the development of technical credentials or certificate programs in partnership with prominent EV manufacturers, which would allow for students and workers to acquire the requisite skills directly from experts in the field.

Participants, particularly regulatory experts, highlighted the necessity of regulatory frameworks that specifically address the environmental and safety aspects of EV battery remanufacturing. Battery remanufacturing is typically not explicitly addressed by current regulations, which are generally broad in scope. Consequently, it is recommended that the government collaborate with industry stakeholders to develop enforceable and transparent regulations, particularly on environmental sustainability, safety protocols, and quality standards, to regulate the remanufacturing process. International best practices should influence these frameworks, but they should be customized to the unique context of SA's environmental and industrial landscape.

The interviewees reported that the success of EV battery remanufacturing in SA is contingent upon the development of state-of-the-art infrastructure. Battery material recovery and testing are particularly challenging due to the absence of advanced technology and facilities. We suggest implementing government incentives and public–private partnerships to address this issue by constructing state-of-the-art facilities with the most advanced technology. In addition to guaranteeing that SA can satisfy global standards for remanufactured EV batteries, these investments would facilitate more efficient remanufacturing processes.

During interviews with workforce specialists and industry executives, workforce development emerged as a significant theme. To guarantee that the remanufacturing industry has a competent labor force, it is prudent for the government to establish innovative workforce reskilling initiatives in partnership with the private sector. For instance, establishing Mobile Remanufacturing Labs in rural and underserved regions can offer hands-on training opportunities to individuals who may not have simple access to urban centers. This would not only ensure that the benefits of the industry's development are distributed more evenly across the country, but it would also help to create a qualified workforce.

Participants in the interview emphasized the significance of international benchmarking and knowledge exchange to remain current with global advancements in the remanufacturing of EV batteries. To accomplish this, South African stakeholders should seek partnerships with countries with more developed EV remanufacturing industries, such as Germany and China. International conferences, exchange programs for technicians, and joint research projects could facilitate the transmission of cutting-edge knowledge and technologies, thereby ensuring that SA remains competitive in the global market.

4.6. Future Research

Academics may (1) conduct an economic viability evaluation to determine the financial sustainability of EV LIB remanufacturing companies; (2) evaluate the economic benefits like GDP and employment creation may enlighten policymakers and investors; or (3) investigate the logistics and supply chain aspects of EV LIB remanufacturing. This study lays the groundwork for future quantitative research into the economic impact of EV LIB remanufacturing in SA. This research contributes to a new body of knowledge that can guide policy and industry development in both SA and other emerging economies by providing critical insights into the technological, regulatory, and workforce challenges.

5. Conclusions

This research explores SA's potential in used LIBs remanufacturing for sustainable development and circular economy practices. This study analyzes the country's remanufacturing capabilities. It presents analytically derived proactive measures aligned with international standards, emphasizing the essential integration of circular economy principles into this growing sector. The proposed strategic initiatives, such as the Interdisciplinary

Innovation Hub, Mobile Remanufacturing Labs, and training programs like the Virtual Reality Consortium and Circular Economy Institutes, aim to equip the workforce with specialized skills for complex remanufacturing processes. These efforts are crucial for promoting an industry that prioritizes environmental responsibility and stimulates economic growth and job opportunities. The Virtual Reality Consortium, Circular Economy Institutes, and Real-world Challenges Program are suggested to develop a sustainable and circular economy-aligned workforce. The findings emphasize the need for a collaborative strategy involving government, industry, and academics to provide a conducive environment for expanding the EV LIB remanufacturing sector. SA aims to become a leader in this field through continuous collaboration, policy innovation, and technical breakthroughs to realize the industry's full potential. Overall, remanufacturing end-of-life lithium-ion batteries provides SA a significant opportunity to enhance its dedication to sustainability and the circular economy.

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