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REFERENCE MODEL FOR ELECTRIC VEHICLE BATTERY RECOVERY IN A CIRCULAR ECONOMY

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ABSTRACT

Electric vehicle batteries, which use a significant amount of critical materials, have the potential to be a reliable secondary source of those high-value materials at the end of their life to meet future needs. In this paper we present a reference model that can enable the development of new approaches for optimizing the value recovery of these materials. This recovery is made exceedingly complex by several issues. First, the battery supply chain is diverse and complex, featuring a multitude of different battery chemistries for use in electric vehicle batteries, each with unique recovery needs. Additionally, raw materials for the batteries are sourced globally, where each local market may feature market dynamics and regulatory frameworks that vary greatly from place to place. Next, current recycling practices in the US are nascent and often involve grinding the batteries into "black mass" at the end of their use. Other recovery options exist but will require cooperation amongst stakeholder groups. A reference model for battery circularity is a starting point for discussions that could harmonize technical solutions for material and value recovery by identifying points of common interest among stakeholders.

The model of battery circularity presented here illustrates different recovery pathways to circularize electric vehicle batteries, including repurposing, remanufacturing, and recycling. It aids in identifying opportunities for improved circularity of existing battery life cycles and determining gaps in design and manufacturing practices, recovery infrastructure, and standards. In particular, we found critical research gaps in determining the state of health of a battery and a scarcity of investigation into the remanufacturing of batteries and tracking of design information, such as the battery chemistry.

Keywords: Circular economy; Electric vehicle batteries; Standards; Remanufacturing; Recycling; IDEF0

1 INTRODUCTION

Electric vehicles (EV) batteries require critical materials such as lithium, cobalt, and nickel. Acquiring these materials is challenging because many have a high risk of supply chain disruption [1] and associated negative impacts [2]. These challenges are compounded by the fact that EV battery demand is predicted to significantly increase over the next several years [3]. Circular economy (CE), or a "systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value" [4], addresses the challenges of supply chain vulnerability and material sourcing difficulties by offering an alternative economic paradigm that prioritizes product life extension and recovery. Applying CE concepts to EV batteries will allow for the extension of the battery's life and the recovery of valuable materials at the battery's end-of-use (EoU).

While there has been research into extending the life of the battery or recovering materials, the circularizing of EV batteries across the value chain is still in early stages. Björn et al. [5] identified challenges for extending battery life cycles including the broad range of battery chemistries, low resource intensity and process efficiency for lithium recovery in recycling, and safety concerns from material handling. More challenges will also emerge with new chemistries since they will require new recycling processes. Recycling phase research has recently featured in-depth studies of pyrometallurgy and hydrometallurgy processes [7–9] and has outlined the steps currently required to recycle batteries. Studies into repurposing, reusing, and remanufacturing EV batteries [6–8] have demonstrated the infancy of these approaches due to many gaps and uncertainties in implementing these battery life-extending techniques. While examples of repurposing batteries for energy storage exist [9,10], currently no standards or guides outlining the process of repurposing EV batteries are available. Some efforts to

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standardize data representation across the battery life cycle have been initiated. These include the CIRPASS initiative from Europe to standardize the information to collect throughout the life cycle [11], SAE International's work to develop a battery traceability standard for the US [12], NAATBatt International's (The Trade Association for Advanced Battery Technology in North America) role in supporting the development, of advanced battery technology in North America [13], and the Federal Consortium for Advanced Batteries (FCAB) role in ensuring cooperation and coordination across US Government agencies in their advanced battery efforts [14].

This paper provides a reference model to establish clarity around the technical processes needed for battery circularity focusing in on the EoU pathways for battery recovery. As a new area of study, battery circularity research pulls together a broad range of stakeholders with different expertise and perspectives to drive the necessary changes to existing systems [5]. Having a common point of reference will facilitate the coordination of the work. The initial battery circularity model addresses the role of battery design for a CE, material recovery options, information to track for improved recovery, and standards needs for battery circularity. The model will be further developed and used to help identify opportunities, shortcomings, and gaps in existing practices. The EoU pathways to battery recovery are the first step in building a broader life cycle model.

2 MATERIALS AND METHODS

Various scholarly journal articles and reports were referenced to construct this battery circularity model. These are cited throughout the description in the results section. This section describes the construction of EV batteries, the role of circularity through design, the framework to support circularity at the EoU, and the modeling method for building the battery circularity model.

2.1 Electric Vehicle Batteries

In an EV, there are usually two primary types of batteries. One powers the powertrain and is often a lithium-ion battery, and the second powers the auxiliary systems, such as the dashboard lights and satellite navigation. This secondary battery can either be lead-acid or lithium-ion. The discussion in this paper focuses on the battery that powers the powertrain.

The basic building block of an EV battery is the cell, which can be cylindrical, pouch, or prismatic. Several cells are assembled into a module, and a pack consists of multiple modules. Then, the EV battery system consists of a battery pack and elements that control or help the battery run, including the battery management system, cooling system, and battery housing. A generic EV battery construction is shown in Figure 1. However, there are many new EV battery designs consisting of packs made solely of cells without modules.

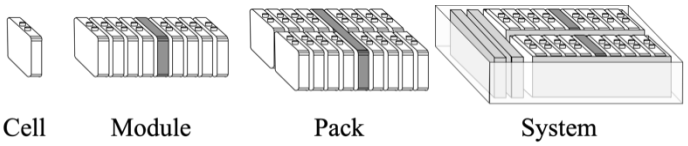

FIGURE 1: EV BATTERY CONSTRUCTION (ADAPTED FROM BSSA [14])

Lithium-ion EV batteries come in a variety of chemistries, including lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium-ion manganese oxide (LMO), lithium nickel cobalt aluminum oxide (NCA), and lithium nickel manganese cobalt oxide (NMC) [15–17]. EV batteries can also have mixed chemistries, such as the 2016 VX e-Golf[1] and 2017 BMW i3 having a battery chemistry of LMO-NCA-NMC or the 2010 and 2015 Nissan Leaf having a battery chemistry of LMO-NCA [17]. Each battery chemistry has advantages and disadvantages, especially related to capacity, energy density, and application [15–17]. These battery chemistries have varying amounts of critical materials with a high risk of supply chain disruption [1] and are associated with upstream impacts [2].

2.2 Circularity through design

Circular product design involves designers planning for a product's life extension, resource efficiency, and recovery during its conceptualization, all while evaluating sustainability trade-offs [18]. As design touches all parts of the product experience, its importance cannot be understated in transitioning to a CE. Generalizable principles of design for circularity can serve as a basis for education or a distilled set of best practices for the early design stages. EV batteries are no exception to a push for increased circularity. By applying several key principles of circular product design, an engineer can have a great influence on the circular potential of EV batteries.

This paper focuses on three specific EoU pathways and overarching design principles for EV battery circularity – design for reuse, design for remanufacture, and design for recycling. We identified three principles as critical to achieving battery circularity:

1. Enable easy inspection, functionality verification, and diagnosis
2. Enable easy disassembly and reassembly
3. Design for reuse in new contexts

Principle 1 is directly linked to determining an EV battery's state of health (SOH). A battery's SOH can determine its remaining useful life and is an important step in appropriating reuse pathways and necessary remanufacturing practices. Furthermore, digital product passports (DPPs), which will be required for EV batteries sold in the European Union (EU) starting in February 2027 [6], are defined as a data infrastructure to operationalize this principle [19] by providing a mechanism to digitally capture information. Information can be tracked with

[1] The commercial products and terms identified in this paper do not imply recommendation or endorsement by NIST. Nor does it imply that they are necessarily the best available for the purpose.

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a DPP that will assist in determining a battery's SOH. With respect to principle 2, EV batteries need to be efficiently and cost-effectively disassembled and reassembled by manufacturing and service professionals. Without this capability, life extension activities such as reuse and remanufacturing become, at worst, impossible and, at best, disincentivized as labor costs for these pathways could rise [7,8]. Furthermore, ease of disassembly can help battery recyclers reclaim the highest percentage of valuable materials possible. Finally, principle 3 addresses a battery's future potential life. For example, the prolonged use of an EV battery leads to an increase in its internal resistance and may cause issues with thermal management [7]. As a result, EV battery designers can support the secondary use of the batteries, such as by specifying appropriate lower voltage applications for subsequent applications of the batteries or detailing how battery cells can fit into modular frames that meet more intense cooling needs.

2.3 Circularity at the End-of-Life

Circularizing products requires a life cycle perspective. The preceding section highlighted the importance of design in enabling circularity since product design can play a pivotal role in enabling product recovery at the EoU stage. Recovery strategies can vary depending on the degree of disassemblability and the material composition of the given product (both functions of design). These techniques align with recovery strategies as identified in the new ISO standards on CE [4]. Optimizing recovery strategies in these ways align with CE principles articulated by Konietzko et al. [20] of "slowing, closing and narrowing material loops". ISO 59004:2024 [4] recommends specific actions to address effective resource management, which are based on what is often referred to as the 'waste hierarchy' [21]. The guidelines defined in the standard provide a consistent means of implementing effective circularity practices. These are applicable not just at the EoU stage for managing 'discarded' products but also for identifying potential opportunities that support circular product design, enabling an iterative process that promotes circular thinking.

In the case of EV batteries, a significant duration of useful life often remains once an EV battery reaches the end of its first use in a vehicle [21]. EV batteries rely on a variety of high-value materials, making it essential to implement proper EoU handling. In addition, EV batteries may be classified as hazardous and may require specialized handling guidelines. Clear guidelines and effective DPPs can help dismantlers facilitate suitable recovery strategies for a given EV battery based not only on its SOH but also type, composition, operational integrity, structural integrity, and material handling requirements.

2.4 IDEF0 Modeling Method

This paper presents a reference model for EV battery recovery using IDEF0. IDEF0 is a modeling language used to illustrate the functions within a system or subject area and is defined by ISO/IEC/IEEE 31320 [22]. The IDEF0 method enables modeling activities, also known as functions, in terms of inputs, controls, outputs, and mechanisms (see Figure 2). Inputs are flows that are acted upon by the activity and produce output flows. Controls define conditions to ensure correct outputs are generated, and mechanisms are the methods and means to complete the activity.

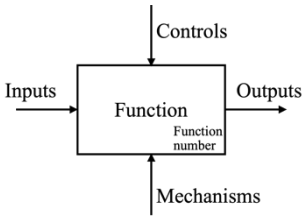

FIGURE 2: IDEF0 GUIDE

Another key feature of the IDEF0 diagramming technique is its support for abstraction. In an IDEF0 model, each function or activity can be decomposed into a subset of functions. For connectivity of the diagrams, the decomposed activity is labeled according to its composite number followed by a new unique number. For instance, a function labeled A1 can be decomposed into a set of functions labeled A1x, where x is incremented for each new function in the decomposition. This feature allows for meaningful discussion at several levels of detail. Functions that are decomposed are highlighted with a shadow.

These models provide insight into the steps and functions within a process. While they do not include values or quantities, they can be used to inform other models that are more quantitative in nature, such as a production risk analysis [23], life cycle assessment [24,25], or a life cycle cost analysis [24].

3 RESULTS

The battery circularity model presented in this paper is adapted from the manufacturing-based CE model developed at the National Institute of Standards and Technology (NIST) [26], which lays out five activities for manufacturing in a CE. Mathur et al. [27] expanded *Treat at End of Life* (activity A5) to provide more details on that function. Currently, the battery circularity model focuses on the treatment at the EoU for EV batteries, which corresponds to the *Treat at End of Life* (activity A5) of the manufacturing CE model. Future work will expand the battery circularity model to include other phases of the battery life cycle.

The top level of the model (A1), shown in Figure 3, consists of collection, sorting, and treatment. Besides "captured batteries," inputs also include "new battery cells or modules" and "new other battery components," which are used elsewhere to replace damaged components. Activity A13 *Treat end-of-life batteries* consists of three processes: *Prepare Battery* (A131), *Repurpose and Remanufacture* (A132), and *Recycle* (A133) (see Figure 4). *Prepare Battery* (see Figure 5) starts with checking the battery's SOH. The SOH is a way to estimate the degradation of the battery and informs which EoU route is preferred for the battery [9,28]. SOH is related to the battery capacity and the nominal capacity. After the SOH is determined, the battery is discharged to allow for safe handling and then disassembled into reusable components (including modules and cells) and damaged components. The battery is discharged after the SOH test since

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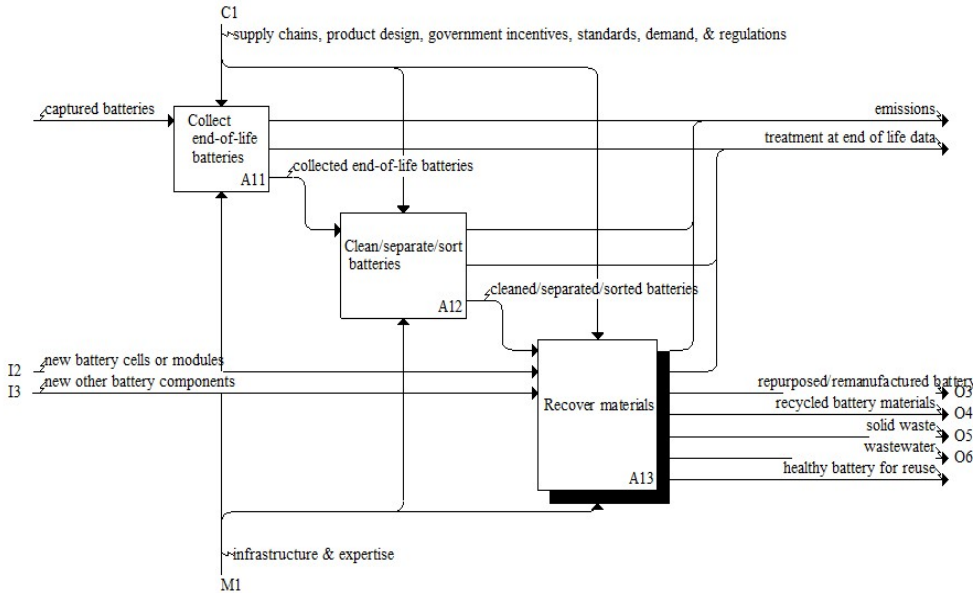

FIGURE 3: DECOMPOSITION OF TREAT AT END OF LIFE ACTIVITY (A1)

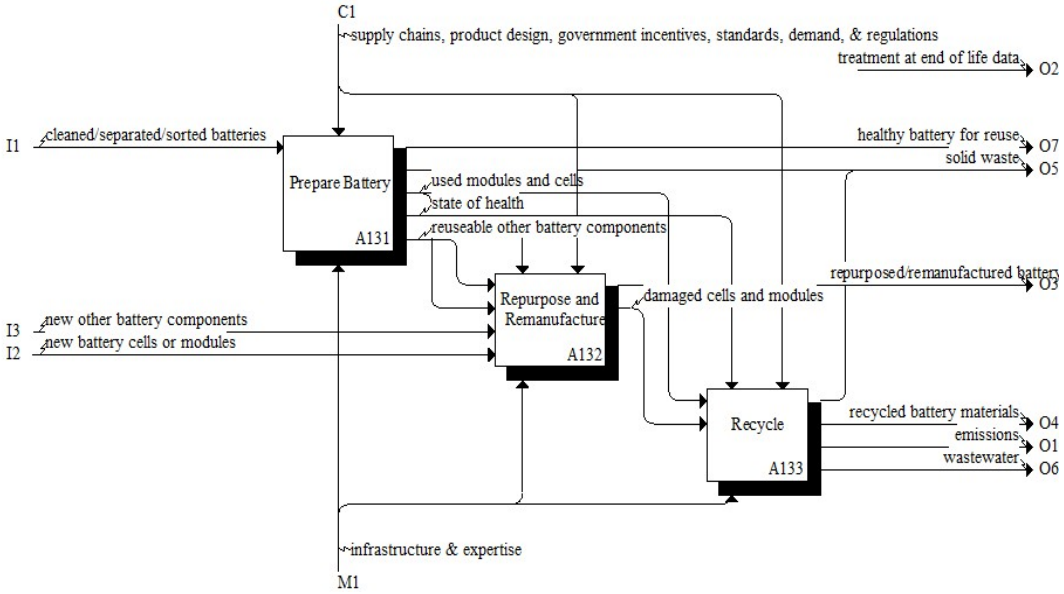

FIGURE 4: DECOMPOSITION OF RECOVER MATERIALS ACTIVITY (A13). SOH GREATLY INFLUENCES THE RECOVERY ROUTE [8,21].

determining SOH may require discharging and recharging the battery.

After the battery is disassembled, it can either go to the *Repurpose and Remanufacture* activity or the *Recycle* activity, depending on its SOH [9,28]. Currently, no standards exist to determine when to remanufacture a battery versus repurposing or recycling. However, Canals Casals et al. [28] provide the guidelines that if the SOH is greater than 88%, then it can be used in an EV as is; if it is less than 88% but greater than 75%, the battery can go to a direct reuse strategy for a second life, and if it's less than 75% the battery should go to a dismantling strategy for a second life. While Canals Casals et al. [28] state batteries can be directly reused, some processing is required before use in a new application. However, UL 1974 is a safety standard used by the US industry to evaluate a battery's safety, condition, and energy capacity intended for repurposing [29].

Repurposing and remanufacturing of an EV battery are covered by the same activity in the model since the steps to accomplish both are similar [6–8]. The differences come in based on the intended application of the recovered battery, i.e., whether the battery will be used for an EV (remanufacturing) or another purpose (repurposing) [8]. To be used in an EV, the battery will need to have sufficient capacity to support EV use. Otherwise, it can be used in a less demanding application, such as stationary

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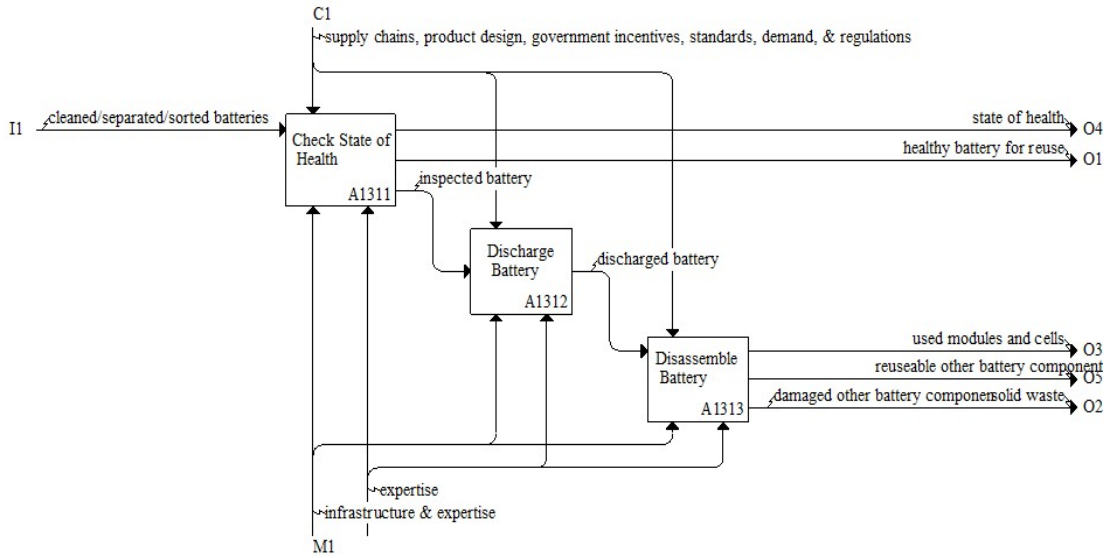

FIGURE 5: DECOMPOSITION OF PREPARE BATTERY ACTIVITY (A131)

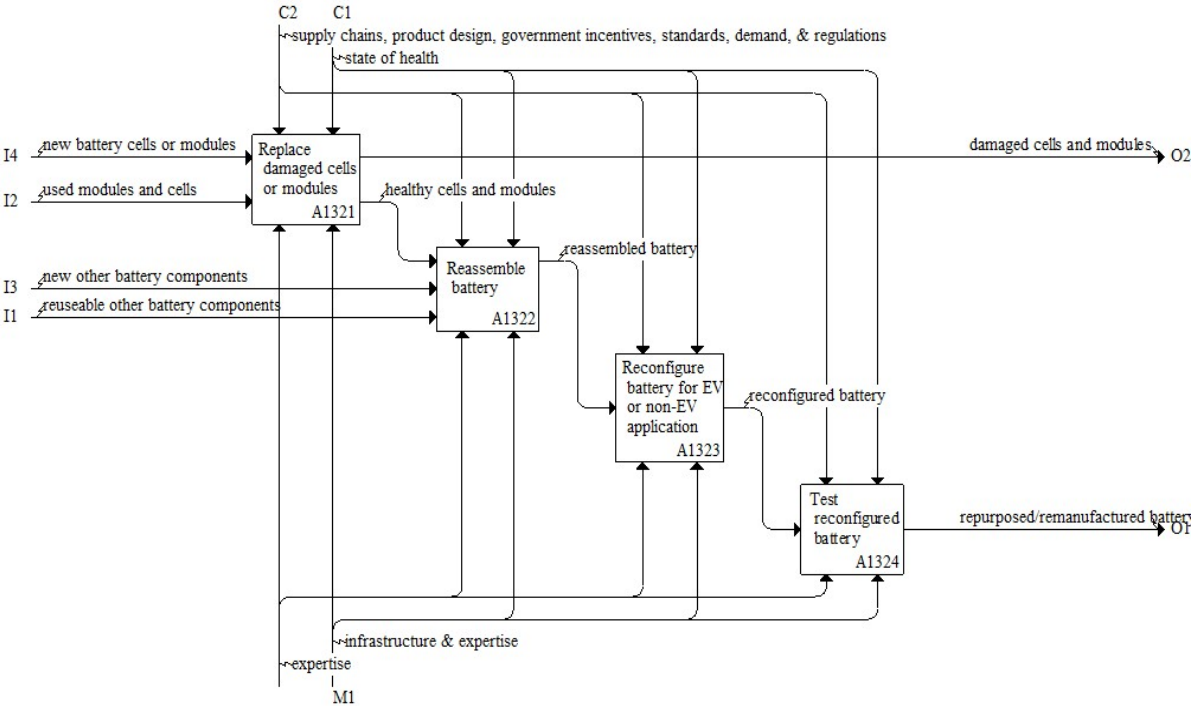

FIGURE 6: DECOMPOSITION OF REPURPOSE AND MANUFACTURE BATTERY ACTIVITY (A132). RECOVERY ROUTE DEPENDS ON BATTERY APPLICATION

storage. *Repurpose and Remanufacture* (see Figure 6) consists of first replacing the damaged cells and modules. Then, the battery is reassembled. Following that, the battery is reconfigured for its new application. This step includes adding a new battery management system. Finally, to conclude the remanufacturing or repurposing process, the battery is tested to confirm it is operating properly and can be used in its designated application.

If the battery does not have a high enough SOH to be remanufactured or repurposed, as determined during the *Prepare Battery* activity, it is recycled. EV battery recycling consists of pyrometallurgy, hydrometallurgy, and a combination of pyrometallurgy and hydrometallurgy (see Figure 7) [9,15,30]. In the US, battery recycling is still nascent. The pyrometallurgy and hydrometallurgy recycling plants are at the pilot scale. Other recycling methods at lab scale include direct recycling methods, which are being developed through ReCell at Argonne National Lab, biohydrometallurgy, and electrometallurgy [30,31]. For pyrometallurgy and hydrometallurgy, the battery materials are

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pretreated, which may include mechanical shredding producing black mass or thermal pretreatment. After the pretreatment, the battery materials then go through the pyrometallurgy process, hydrometallurgy process, or a combination of both.

Pyrometallurgy is a thermal process in which the materials of interest are separated from the slag and concentrated [31]. The recovered materials for pyrometallurgy (see Figure 8) include iron, copper, nickel, and lithium compounds; however, lithium recovery is currently uncommon [30]. The hydrometallurgy process (see Figure 9) involves using aqueous solutions to treat complex compositions and recover low-concentration metals but at a high purity [31]. Other metals, including manganese compounds and the anode, also can be recovered [30] through this recovery process.

4 DISCUSSION

In constructing this model, some observations reflect on the information to track and improve the circularity of the EV batteries. These items include the chemistry and the materials in the battery. This information can support better design of recovery processes to recapture a greater percentage of the battery materials. Currently, when batteries are shredded, the exact composition of the resulting black mass is unknown since each battery may have a different chemistry [32]. This impacts the ability to recycle the black mass since recycling processes are designed for specific chemistries to recover the highest quality and quantity of the materials [31]. In addition, awareness of the materials in the batteries will improve safety since chemicals within the black mass may be hazardous to human health. Currently, handlers of black mass may not know what is in it and, therefore, must treat it as hazardous, even though the black mass may not be. Providing clarity as to what is in the black mass and better definitions to classify various types of black mass as hazardous will improve safety and reduce transportation and handling costs [33].

Further, tracking important events during battery use, such as the battery being involved in a crash or overheating, will improve the accuracy of the SOH assessment [34]. If the SOH is unknown, battery handlers are required to treat the battery as damaged, defective, or recalled (DDR), which can add significant costs to the packaging or transportation [33].

Having the battery's mechanical design or disassembly instructions will also improve disassembly at the EoU. Improved disassembly will increase the value recovered from the battery through repurposing, remanufacturing, or recycling [7,8].

Tracking information for regulatory purposes may also be desired. In the US, for manufacturers and customers to be eligible for tax incentives, an increasing percentage of the value of the vehicle's battery components must be manufactured or assembled in North America [35], including material that originally came from outside the US but was recycled in the US. Tracking will aid companies in demonstrating that their batteries meet this requirement. In addition, starting in February 2027 [6], the EU will require that all batteries greater than 2kWh sold in the EU have a DPP associated with them, and since the majority of EV battery companies are multinational, US-based companies will be affected by this requirement. This DPP will contain materials and composition, circularity and resource efficiency, and other battery information [6].

While this work provides a reference for pursuing an idealized recovery system for EV batteries, several assumptions made still involve unresolved challenges. Measuring the SOH has many challenges, and much more work is needed [34]. Currently, the SOH cannot be determined with the infrastructure and expertise available to recoverers. The capacity can only be measured in a laboratory setting while performing a full battery

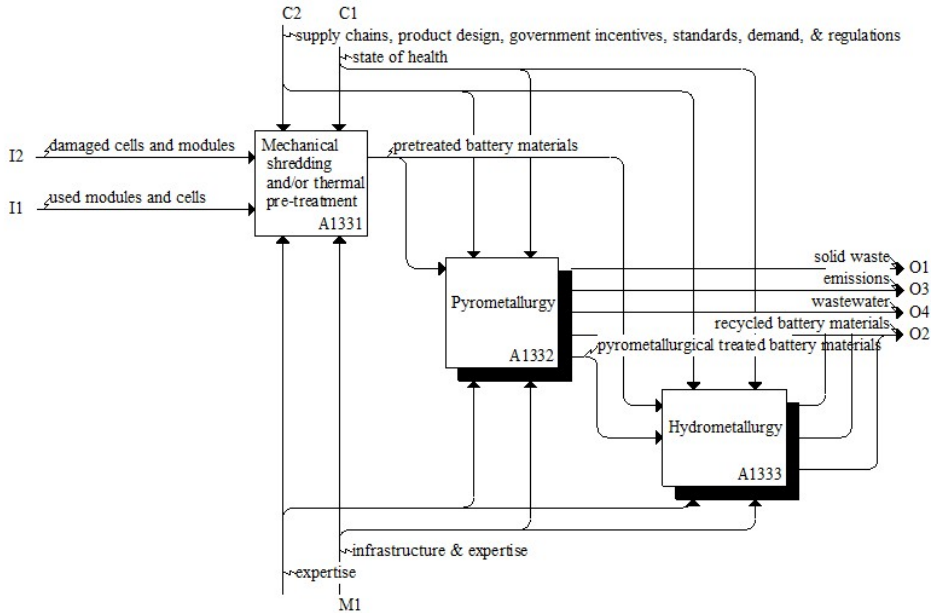

FIGURE 7: DECOMPOSITION OF RECYCLE (A133)

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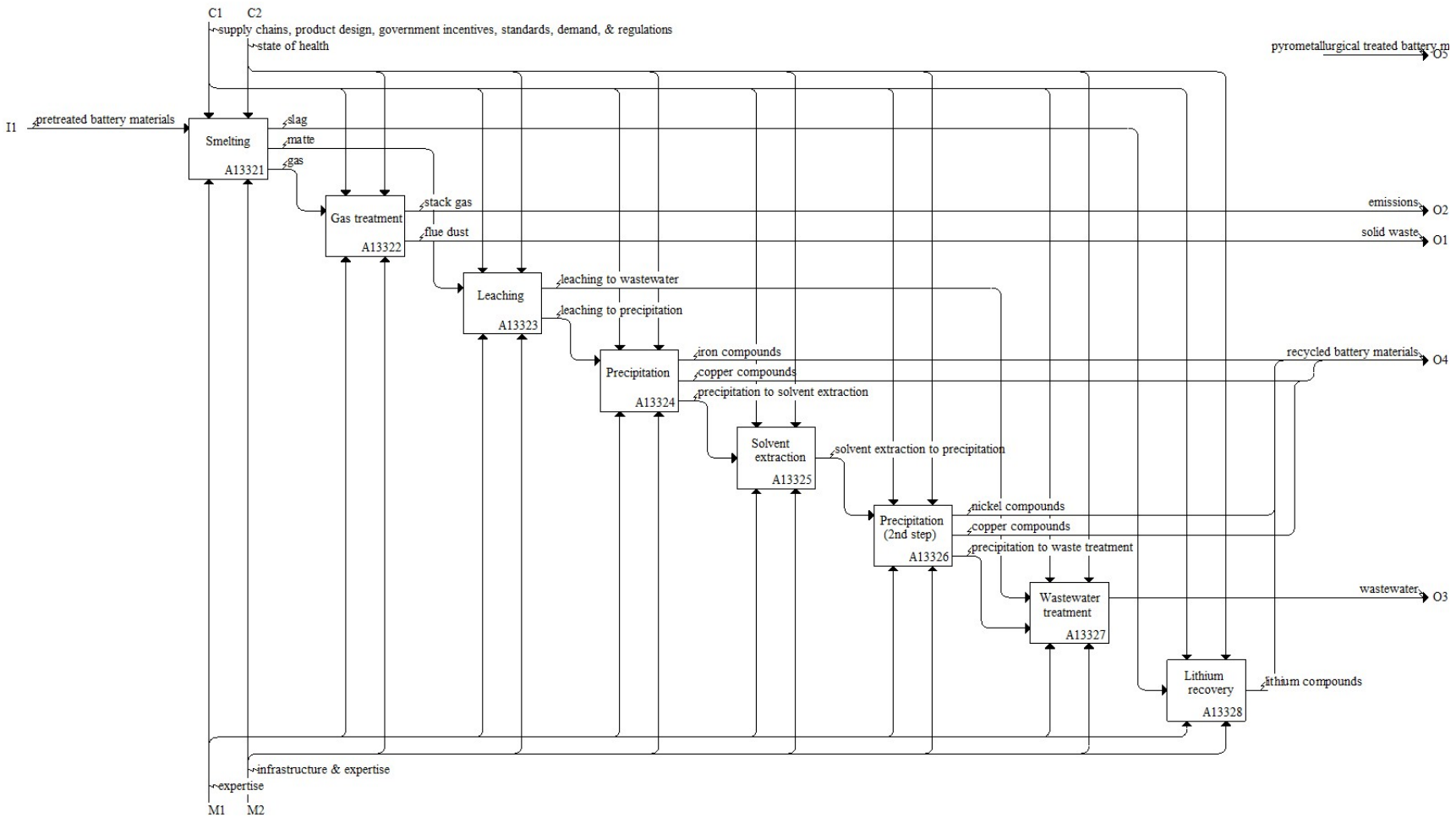

FIGURE 8: ACTIVITIES WITHIN A GENERIC PYROMETALLURGY RECYCLING PROCESS (A1332)

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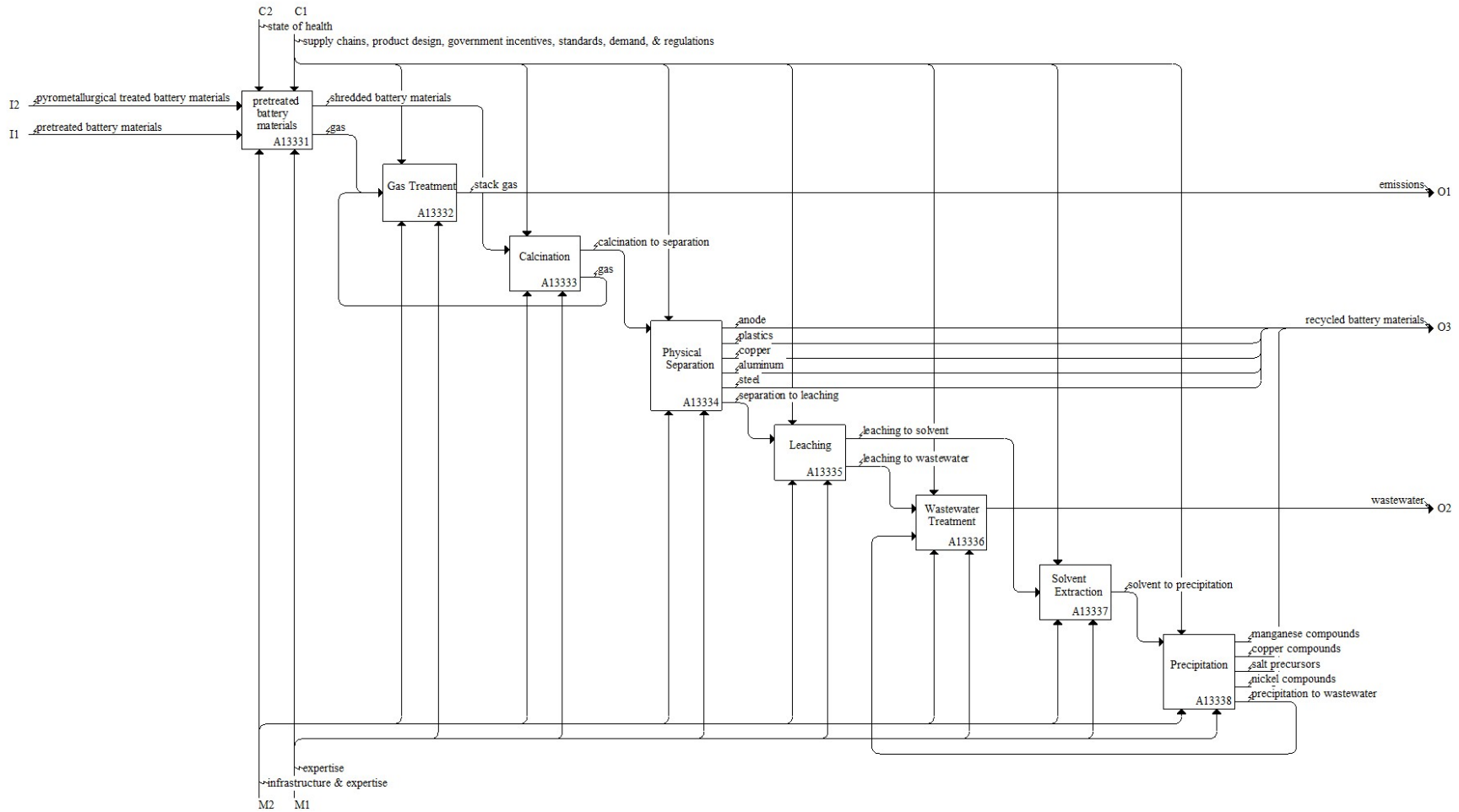

FIGURE 9: ACTIVITIES WITHIN A GENERIC HYDROMETALLURGY RECYCLING PROCESS (A1333)

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discharge and charge. It cannot be determined while the battery is in the vehicle. Some algorithms and machine learning techniques, such as neural networks, gaussian prosses regression, and support vector regression, have been proposed to simplify determining the SOH [34]. These methods do not require removing the battery from the vehicle and can use health indicators can be taken from the battery management system or measured directly. These health indicators include voltage, current, and ambient temperature profiles, full-cycle battery discharge profiles, and the change in voltage after the EV is turned off.

Challenges in recycling batteries arise due to the many chemistries used in EV batteries, that can vary from manufacturer to manufacturer [9]. Manufacturers are moving away from cobalt to higher nickel chemistries, which weakens the existing battery recycling business models that rely heavily on recovering high-value cobalt. In addition, chemistries may also be mixed and are constantly evolving [9,17]. All these challenges make it difficult to recover a consistent material quality and makes recycling less valuable. Having standard battery design processes may lessen the burden on recovery activities, making planned recovery more practicable.

Further research and standards activities are needed to make battery repurposing a widespread practice. Some examples of battery repurposing include the integration of Nissan Leaf batteries with solar power to provide energy to Amsterdam's Johan Cruijff Arena and Chevy Volt batteries with solar arrays and wind turbines to power General Motors' Enterprise Data Center in Milford, Michigan [9,10]. Standards that help manufacturers determine when batteries are fit for repurposing and remanufacturing can scale up those practices across the industry. Standards can provide guides and best practices for repurposing batteries and health indicators for determining the preferred recovery route (i.e., remanufacture, repurpose, or recycle). Recycling of EV batteries is also still in its infancy. Early batteries have lasted longer than expected [36], resulting in a lower supply of batteries to be recycled than predicted. This has limited recyclers' ability to project the return needed to invest in infrastructure for recovering valuable materials from EV batteries.

5 CONCLUSION

This paper provided an initial reference model for EV battery recovery to identify opportunities for circularizing existing battery lifecycles. From constructing this model, we found needs for determining the SOH of a battery and a scarcity of investigation into the remanufacturing of batteries. This model identifies requirements for battery design for CE, guidance around material selection, information to track, and standards needs for better circularity. The model acts as a first step to clearly and openly articulating the entire life cycle for battery production and recovery. It forms the basis for a shared understanding of the life cycle as we collectively move forward towards greater circularity. As such, future work includes expanding the reference model to include the other stages of the battery life cycle and validating with use cases.

REFERENCES

[1] US Department of Energy, 2023, *Notice of Final Determination on 2023 DOE Critical Materials List*. [Online]. Available: https://www.federalregister.gov/d/2023-16611. [Accessed: 22-Oct-2024].

[2] Sharma, S. S., and Manthiram, A., 2020, "Towards More Environmentally and Socially Responsible Batteries," Energy Environ. Sci., **13**(11), pp. 4087–4097. https://doi.org/10.1039/D0EE02511A.

[3] BloombergNEF, 2024, *Electric Vehicle Outlook 2024*. [Online]. Available: https://about.bnef.com/electric-vehicle-outlook/. [Accessed: 13-Mar-2025].

[4] International Organization for Standardization (ISO), 2024, *ISO 59004:2024(En) Circular Economy — Vocabulary, Principles and Guidance for Implementation*, International Organization for Standardization, Geneva, CH.

[5] Johansson, B., Despeisse, M., Bokrantz, J., Braun, G., Cao, H., Chari, A., Fang, Q., González Chávez, C. A., Skoogh, A., Söderlund, H., Wang, H., Wärmefjord, K., Nyborg, L., Sun, J., Örtengren, R., Schumacher, K. A., Espinal, L., Morris, K. C., Nunley, J., Kishita, Y., Umeda, Y., Acerbi, F., Pinzone, M., Persson, H., Charpentier, S., Edström, K., Brandell, D., Gopalakrishnan, M., Rahnama, H., Abrahamsson, L., Rönnbäck, A. Ö., and Stahre, J., 2024, "Challenges and Opportunities to Advance Manufacturing Research for Sustainable Battery Life Cycles," Frontiers in Manufacturing Technology, **4**. https://doi.org/10.3389/fmtec.2024.1360076.

[6] Wautelet, T., and Ayed, A.-C., 2024, "Exploring Possible Digital Product Passport (DPP) Use Cases in Battery, Electronics and Textile Value Chains." https://doi.org/10.5281/ZENODO.10974901.

[7] Kampker, A., Wessel, S., Fiedler, F., and Maltoni, F., 2021, "Battery Pack Remanufacturing Process up to Cell Level with Sorting and Repurposing of Battery Cells," Jnl Remanufactur, **11**(1), pp. 1–23. https://doi.org/10.1007/s13243-020-00088-6.

[8] Hua, Y., Liu, X., Zhou, S., Huang, Y., Ling, H., and Yang, S., 2021, "Toward Sustainable Reuse of Retired Lithium-Ion Batteries from Electric Vehicles," Resources, Conservation and Recycling, **168**, p. 105249. https://doi.org/10.1016/j.resconrec.2020.105249.

[9] Chen, M., Ma, X., Chen, B., Arsenault, R., Karlson, P., Simon, N., and Wang, Y., 2019, "Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries," Joule, **3**(11), pp. 2622–2646.

[10] Sheehan, S., 2018, "Nissan Leaf Batteries Power Dutch Stadium's Energy Storage System," Autocar. [Online]. Available: https://www.autocar.co.uk/car-news/business/nissan-leaf-batteries-power-dutch-stadiums-energy-storage-system. [Accessed: 23-Oct-2024].

[11] "CIRPASS – Digital Product Passport," CIRPASS Digital Product Passport. [Online]. Available: https://cirpassproject.eu/. [Accessed: 03-Mar-2025].

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[12] SAE International, "Battery Global Traceability Standards Committee - SAE StandardsWorks." [Online]. Available: https://standardsworks.sae.org/standards-committees/battery-global-traceability-standards-committee. [Accessed: 03-Mar-2025].
[13] "NAATBatt International." [Online]. Available: https://naatbatt.org/. [Accessed: 03-Mar-2025].
[14] "Federal Consortium for Advanced Batteries (FCAB)," Energy.gov. [Online]. Available: https://www.energy.gov/mesc/federal-consortium-advanced-batteries-fcab. [Accessed: 03-Mar-2025].
[15] Baum, Z. J., Bird, R. E., Yu, X., and Ma, J., 2022, "Lithium-Ion Battery Recycling─Overview of Techniques and Trends," ACS Energy Lett., **7**(2), pp. 712–719. https://doi.org/10.1021/acsenergylett.1c02602.
[16] Blomgren, G. E., 2017, "The Development and Future of Lithium Ion Batteries," J. Electrochem. Soc., **164**(1), pp. A5019–A5025. https://doi.org/10.1149/2.0251701jes.
[17] Schmuch, R., Wagner, R., Hörpel, G., Placke, T., and Winter, M., 2018, "Performance and Cost of Materials for Lithium-Based Rechargeable Automotive Batteries," Nat Energy, **3**(4), pp. 267–278. https://doi.org/10.1038/s41560-018-0107-2.
[18] Hapuwatte, B. M., and Jawahir, I. S., 2021, "Closed-loop Sustainable Product Design for Circular Economy," J of Industrial Ecology, **25**(6), pp. 1430–1446. https://doi.org/10.1111/jiec.13154.
[19] Berger, K., Schöggl, J.-P., and Baumgartner, R. J., 2022, "Digital Battery Passports to Enable Circular and Sustainable Value Chains: Conceptualization and Use Cases," Journal of Cleaner Production, **353**, p. 131492. https://doi.org/10.1016/j.jclepro.2022.131492.
[20] Konietzko, J., Bocken, N., and Hultink, E. J., 2020, "Circular Ecosystem Innovation: An Initial Set of Principles," Journal of Cleaner Production, **253**, p. 119942. https://doi.org/10.1016/j.jclepro.2019.119942.
[21] Mathur, N., Deng, S., Singh, S., Yih, Y., and Sutherland, J. W., 2019, "Evaluating the Environmental Benefits of Implementing Industrial Symbiosis to Used Electric Vehicle Batteries," Procedia CIRP, **80**, pp. 661–666. https://doi.org/10.1016/j.procir.2019.01.074.
[22] ISO, 2012, "Information Technology — Modeling Languages — Part 1: Syntax and Semantics for IDEF0." [Online]. Available: https://www.iso.org/standard/60615.html.
[23] Collier, Z. A., Gaskins, A., and Lambert, J. H., 2023, "Business Process Modeling for Semiconductor Production Risk Analysis Using IDEF0," IEEE Eng. Manag. Rev., **51**(1), pp. 183–188. https://doi.org/10.1109/EMR.2022.3230374.
[24] Zhang, H., Haapala, K. R., Vanlue, M. E., and Funk, K. H., 2011, "Environmental Impact and Cost Assessment of Product Service Systems Using IDEF0 Modeling." https://doi.org/10.13140/2.1.1552.4488.
[25] Luglietti, R., Rosa, P., Terzi, S., and Taisch, M., 2016, "Life Cycle Assessment Tool in Product Development: Environmental Requirements in Decision Making Process," Procedia CIRP, **40**, pp. 202–208. https://doi.org/10.1016/j.procir.2016.01.103.
[26] Reslan, M., Last, N., Mathur, N., Morris, K., and Ferrero, V., 2022, "Circular Economy: A Product Life Cycle Perspective on Engineering and Manufacturing Practices," Procedia CIRP, **105**, pp. 851–858. https://doi.org/10.1016/j.procir.2022.02.141.
[27] Mathur, N., Last, N., and Morris, K. C., 2023, "A Process Model Representation of the End-of-Life Phase of a Product in a Circular Economy to Identify Standards Needs," Front. Manuf. Technol., **3**, p. 988073. https://doi.org/10.3389/fmtec.2023.988073.
[28] Canals Casals, L., Amante García, B., and Cremades, L. V., 2017, "Electric Vehicle Battery Reuse: Preparing for a Second Life," JIEM, **10**(2), p. 266. https://doi.org/10.3926/jiem.2009.
[29] UL Standards & Engagement, 2023, *UL 1974 Evaluation for Repurposing or Remanufacturing Batteries*.
[30] Dai, Q., Spangenberger, J., Ahmed, S., Gaines, L., Kelly, J. C., and Wang, M., 2019, *EverBatt: A Closed-Loop Battery Recycling Cost and Environmental Impacts Model*, Argonne National Laboratory (ANL), Argonne, IL (United States).
[31] Martins, L. S., Guimarães, L. F., Botelho Junior, A. B., Tenório, J. A. S., and Espinosa, D. C. R., 2021, "Electric Car Battery: An Overview on Global Demand, Recycling and Future Approaches towards Sustainability," Journal of Environmental Management, **295**, p. 113091. https://doi.org/10.1016/j.jenvman.2021.113091.
[32] Gianvincenzi, M., Mosconi, E. M., Marconi, M., and Tola, F., 2024, "Battery Waste Management in Europe: Black Mass Hazardousness and Recycling Strategies in the Light of an Evolving Competitive Regulation," Recycling, **9**(1), p. 13. https://doi.org/10.3390/recycling9010013.
[33] US Department of Energy, 2024, *Bridging the U.S. Lithium Battery Supply Chain Gap: Forum on Li-Ion Battery Recycling and End-of-Life Batteries*, Argonne National Laboratory. [Online]. Available: https://www.anl.gov/access/reference/bridging-the-us-lithium-battery-supply-chain-gap-forum-on-liion-battery-recycling-and-endoflife.
[34] Etxandi-Santolaya, M., Canals Casals, L., Montes, T., and Corchero, C., 2023, "Are Electric Vehicle Batteries Being Underused? A Review of Current Practices and Sources of Circularity," Journal of Environmental Management, **338**, p. 117814. https://doi.org/10.1016/j.jenvman.2023.117814.
[35] US Department of Energy, "Electric Vehicle (EV) and Fuel Cell Electric Vehicle (FCEV) Tax Credit." [Online]. Available: https://afdc.energy.gov/laws/409. [Accessed: 22-Oct-2024].
[36] Najman, L., 2024, "New Updates: How Long Do Electric Car Batteries Last?," Recurrent. [Online]. Available: https://www.recurrentauto.com/research/how-long-do-ev-batteries-last. [Accessed: 25-Oct-2024].

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