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ELECTRIC VEHICLE BATTERY END-OF-LIFE MANAGEMENT

Information Sharing Gaps and the Current State of Practice

BUSINESS WHITE PAPER

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Supply Chain (SC) Working Group

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EXECUTIVE SUMMARY

Various proposed regulations in the European Union (EU), United States (US), and other global regions will require information sharing about electric vehicle (EV) batteries between supply chain stakeholders, regulators, and end-users at an unprecedented level throughout the lifecycle of batteries, such that changes to battery data can be tracked.

This document focuses on information sharing between supply chain entities during the EV battery's end-of-life (EOL), including an evaluation of the parties responsible for EOL management.

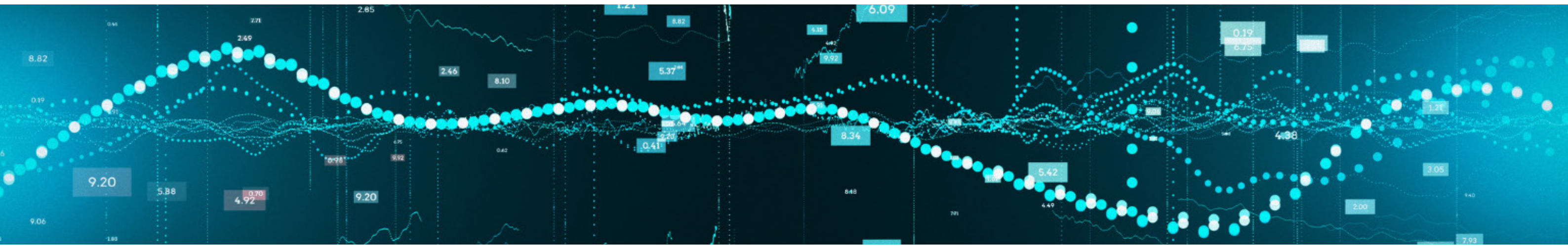
This document focuses on information sharing between supply chain entities during the EV battery's end-of-life (EOL), including an evaluation of the parties responsible for EOL management and the kinds of information they produce and share with their trading partners. This document also identifies information gaps that could hinder compliance with proposed regulations.

This document proposes various strategies to bridge information gaps, including the use of battery passports to share battery EOL data.

Finally, this document proposes various strategies to bridge those information gaps, including the use of battery passports to share battery EOL data. The authors of this document believe that MOBI's Implementation Guidelines for a Decentralized Cross-Border Compliant Solution (June 2023) will play an essential role in facilitating battery data sharing in compliance with proposed regulations and offers a necessary foundation for stakeholders to meet their objectives of circularity and sustainability across the EV battery lifecycle.

LIST OF ACRONYMS

BMS	:	Battery Management System
CalEPA	:	California Environmental Protection Agency
EOL	:	End-of-Life
EU	:	European Union
EV	:	Electric Vehicle
LiB	:	Lithium Ion Battery
OEM	:	Original Equipment Manufacturer
SOC	:	State of Charge
SOH	:	State of Health
US	:	United States
USD	:	United States Dollar



GLOSSARY OF TERMS

This section contains the definitions of all technical and specific terms used throughout this document.

Battery: Any source of electrical energy generated by direct conversion of chemical energy and consisting of one or more non-rechargeable or rechargeable battery cells or of groups of them.

Battery Cell: A battery cell is the basic unit of a battery, responsible for storing and releasing electrical energy. A battery cell comprises three primary components: the positive electrode (anode), the negative electrode (cathode), and the electrolyte.

Battery Management System (BMS): A battery management system manages a battery pack and monitors the operating state of modules and cells, calculates and reports various performance data, and balances the performance of individual cells and modules.

Battery Passport: A battery passport is a digital record that provides comprehensive, traceable information about a battery's lifecycle, from manufacturing to end-of-life. It includes data on the materials used, production methods, ownership history, performance metrics, and recycling instructions. This transparent and standardized documentation aims to ensure sustainability, enhance safety, and facilitate efficient recycling and reuse, contributing to a circular economy and responsible resource management in the battery industry.

Battery State of Charge (SOC): The Battery State of Charge is the remaining capacity/total capacity or rated capacity. As the battery ages, remaining capacity decreases.

Battery State of Health (SOH): The Battery State of Health is the ratio of total maximum capacity (in kWh) at any given time over beginning of life capacity (or rated capacity). The SOH deteriorates over long periods of usage impacting the battery's overall performance.

California Environmental Protection Agency (CalEPA): California Environmental Protection Agency consists of the California Air Resources Board (CARB), the Department of Pesticide Regulation (DPR), the Department of Resources Recycling and Recovery (CalRecycle), the Department of Toxic Substances Control (DTSC), the Office of Environmental Health Hazard Assessment (OEHHA), and the State Water Resources Control Board (SWRCB).

Electric Vehicle (EV): An Electric Vehicle is defined as a vehicle that can be powered by an electric motor that draws electricity from a battery and is capable of being charged from an external source. An EV includes both a vehicle that can only be powered by an electric motor that draws electricity from a battery (all-electric vehicle) and a vehicle that can be powered by an electric motor that draws electricity from a battery and by an internal combustion engine (plug-in hybrid electric vehicle).

End-of-life (EOL): End-of-life of a product occurs when it reaches the end of its life cycle. When a product reaches EOL, it has reached the end of its useful life and is retired. Depending on the product and its condition at EOL it can be recycled, repurposed or sent to disposal.

Lithium-Ion Battery (LiB): A lithium ion battery is a type of rechargeable battery technology that leverages the unique properties of lithium, the lightest of all metals.

Module: A battery module is a unit composed of multiple battery cells assembled together to provide higher voltage and capacity. It is a component of a battery system and typically consists of several battery cells, connectors, a Battery Management System (BMS), and an enclosure.

Original Equipment Manufacturer (OEM): An Original Equipment Manufacturer is an organization that makes devices from component parts either made internally or sourced from other organizations.

OBJECTIVE OF THIS DOCUMENT

Efficient, end-to-end information sharing and traceability throughout the EV battery lifecycle demonstrates transparency and compliance with various battery regulations, enabling an audit trail for trading partners, end-users, and regulators.

Efficient, end-to-end information sharing and traceability throughout the EV battery lifecycle demonstrates transparency and compliance with various battery regulations, enabling an audit trail for trading partners, end-users, and regulators. However, the complexity of the EV battery supply chain has resulted in information sharing gaps that pose obstacles to industry-wide compliance with regulations pertaining to battery recordkeeping and the traceability of materials.

The objectives of this document are twofold:

» To identify the information sharing gaps in EV battery EOL management.

» To provide strategies to bridge those information gaps such that the supply chain members can provide necessary battery information to the general public, regulators, end-users, and other concerned entities such as recyclers and reusers.

In order to identify such gaps, the SC Working Group mapped the current state of practice concerning the recycling, repurposing, and reuse of lithium LiBs installed on EVs.

In order to identify such gaps, the SC Working Group (WG) mapped the current state of practice concerning the recycling, repurposing, and reuse of lithium-ion batteries (LiBs) installed on EVs. As an example, the WG reviewed how the identity of a battery pack is maintained throughout its lifecycle and examined the current state of practice with regard to battery serial number management and unique battery identities. The WG also reviewed current and proposed regulations pertaining to EV battery information sharing. The WG's findings and recommendations are enclosed hereafter.

Discussions in this document are limited to LiBs installed in light, medium, and heavy-duty EVs, as LiBs are the most dominant type of battery chemistry in the current market.

INFORMATION SHARING IN EOL MANAGEMENT

In order for regulators to verify claims, they must be able to "trace" the battery information and the associated data in the provided claims.

The European Union Battery Regulation and the proposed US Treasury's Section 30D Guidance require EV manufacturers and other supply chain members to share battery-related information with their trading partners, end users, and regulators. Both measures require battery supply chain members to not only provide battery information but also prove that the information is accurate and timely. In order for regulators to verify such claims, they must be able to "trace" the battery information and the associated data in the provided claims.

This document analyzes information sharing gaps in the current state of practice and proposes methods to close those gaps in order to maintain information traceability throughout battery recycling, repurposing, and reuse in compliance with current and proposed regulations. "Information sharing" in this document pertains to EV battery supply chain members exchanging data about the state of batteries during the process of EOL management.

"Information sharing" in this document pertains to EV battery supply chain members exchanging data about the state of batteries during the process of EOL management.

In particular, this document analyzes the following with regard to recycling, repurposing, and reuse:

» Identification of responsible supply chain members per the current state of practice and how regulations define the responsible parties that would be held accountable for the timeliness and correctness of battery information.

» Methods of maintaining a battery's identity throughout its lifecycle in compliance with EU regulations (requiring the creation of a new identity when a battery is repurposed and deprecation of identity once the battery is recycled).

» Access management for confidential battery information, such that supply chain members can exercise control over which of their trading partners can access specific data.

» Attestation of information provided by trading partners and manufacturers using digital signatures, and whether such attestations can be verified by the recipients.

EV BATTERY END-OF-LIFE

Battery End-of-Life Definition

A product reaches its EOL when it no longer works as originally intended, when the battery is retired due to damage, and/or no longer operates at a sufficient capacity.

A product reaches its End-of-life (EOL) when it no longer works as originally intended, when the battery is retired due to damage, and/or no longer operates at a sufficient capacity. It is important to note that the EOL here refers to the end of the first life of an EV battery; that is, when the battery becomes unusable as originally intended due to performance degradation, physical damage, or other safety concerns.

A standard concept to specify a battery at EOL has not been unanimously or clearly defined for batteries.

Battery State of Health (SOH) and State of Charge (SOC) are commonly used to measure a battery's performance and determine whether it has reached the end of its intended first use. Battery SOH represents the total maximum capacity at any time over the initial life capacity (rated capacity) of the battery. SOC, on the other hand, is the remaining capacity over total capacity (or rated capacity). SOH degrades over time; an EV battery is generally considered to be at the end of its first useful life when the SOH drops to 70% - 80%. However, a standard concept to specify a battery at EOL has not been unanimously or clearly defined for batteries as they are complex electrochemical systems with nonlinear degradation behaviors.[1] Battery EOL depends on design parameters and the nature of the application, hence determining EOL can be complex.

When a battery reaches the end of its intended use, the responsible party removes the battery from the EV and, following an assessment, determines whether it will go to recycling or to a second-life application through reuse or repurposing.

The Need for EV Battery End-of-Life Management

Battery lifecycle traceability is now more critical than ever due to the rise in global EV sales

EV sales are rising across the globe with changing customer demand and decarbonization related incentives. The number of electric vehicles on the road worldwide reached 16.5 million in 2021.[2] The total number of EVs is projected to reach 700 million by 2050.[3] According to the same report, "all automobile sales in Europe (86%), China (81%) and North America (78%) will predominantly be EVs by 2050". Although this shift to EVs will reduce net carbon emissions, used EV batteries can greatly impact the environment if not properly managed past their first use.

Note: For the purpose of this project, 'EV battery' is defined as any battery specifically designed to provide electric power for the traction to hybrid or electric vehicles of L category as provided for in Regulation (EU) No 168/2013, and with a weight above 25 kg, or designed to provide electric power for the traction to

[1] Arrinda, M.; Oyarbide, M.; Macicior, H.; Muxika, E.; Popp, H.; Jahn, M.; Ganev, B.; Cendoya, I. Application Dependent End-of-Life Threshold Definition Methodology for Batteries in Electric Vehicles. Batteries 2021, 7, 12. https://doi.org/10.3390/batteries7010012

[2] "Electric Vehicles – Analysis." IEA. November 202, IEA. https://www.iea.org/reports/electric-vehicles.

[3] Mackenzie, Wood. 2021. "700 Million Electric Vehicles Will Be on the Roads by 2050." Www.woodmac.com. February 8, 2021. https://www.woodmac.com/press-releases/700-million-electric-vehicles-will-be-on-the-roads-by-2050/.

hybrid or electric vehicles of M, N, or O categories as provided for in Regulation (EU) 2018/858.

Battery reuse and repurposing are also important to achieve circularity and reduce waste and resource depletion.

The phases in an EV battery's life cycle that generate the most emissions and waste involve material sourcing, manufacturing, and end-of-life activities. According to the CalEPA, it is crucial to create a circular battery supply chain and reduce its environmental impact by increasing battery recycling such that raw materials can be extracted for the manufacturing of new EV batteries.[4] Battery reuse and repurposing are also important to achieve circularity and reduce waste and resource depletion.

Lack of regulations, lack of clarity on responsible parties for EOL management, high cost of recycling and geographical factors.

A variety of recycling technologies for EV batteries exist today and more LiB-focused recycling plants are being developed. However, only about 5% of batteries are being recycled.[5] Lack of regulations, lack of clarity on responsible parties for EOL management, high cost of recycling, geographical factors (such as proximity to recyclers), and lack of economic incentives represent a sample of the various obstacles to recycling.

Material Sourcing

Mining of lithium, nickel, and cobalt — critical minerals in LiB production — is detrimental to the environment and often associated with ethical concerns.

Recycling

Another factor contributing to the diminished recyclability of LiBs is the lack of design considerations for recycling in the majority of EV battery systems.

While other types of batteries, such as lead batteries, are mostly recycled (approx. 99% of lead batteries are recycled), it is relatively more difficult and costly to recycle LiBs, as they consist of hundreds of li-ion cells that need dismantling to be recycled, which can be dangerous as the batteries contain hazardous materials.[6]

Another factor contributing to the diminished recyclability of LiBs is the lack of design considerations for recycling in the majority of EV battery systems.[7] When these batteries are not effectively recycled, reused, or repurposed, they often find their way into landfills. This disposal method not only raises concerns of water and soil contamination but also escalates the risk of fires due to the presence of toxic and flammable materials within the batteries.

Current Regulatory Environment

Recent regulation proposals and policymaking efforts in the EU, US, and Asia have incentivized stakeholders in the battery market to identify responsible parties for handling EOL and more.

Recent regulation proposals and policymaking efforts in the EU, US, and Asia have incentivized stakeholders in the battery market to identify responsible parties for handling EOL, increase EV battery recycling, develop more efficient methods of recycling (with higher recovery rates), and design and produce batteries more sustainably.

[4]Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. "Lithium-Ion Car Battery Recycling Advisory Group Final Report." CalEPA. 16 March, 2022, CalEPA. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf.

[5]Woollacott, Emma. "Electric Cars: What Will Happen to All the Dead Batteries?" BBC News, April 26, 2021, sec. Business. https://www.bbc.com/news/business-56574779.

[6]"New Study Confirms U.S.' Most Recycled Consumer Product - Lead Batteries - Maintains Remarkable Milestone: 99% Recycling Rate." Battery Council International. July 12, 2023. https://batterycouncil.org/new-study-confirms-lead-batteries-maintain-remarkable-99-recycling-rate/.

[7]Melin, H. E., "The Lithium-Ion Battery End-of-Life Market -A Baseline Study." n.d. World Economic Forum. https://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf.

United States

There are existing regulations in the US at the federal and state levels to regulate activities that are relevant to the EOL of batteries, but there are currently no holistic, overarching policies for batteries at their EOL, and it is ambiguous how used LiBs are legally defined in terms of waste.[8]

In the US, used batteries are generally considered hazardous or universal waste, which are then bound to existing waste regulations. Regulations also vary by jurisdiction. The most stringent regulations include the US federal hazardous waste laws and regulations, which are related to the generation, handling, storage, treatment, domestic or international transport, and disposal of hazardous wastes.[9] The US also lacks regulations on sharing traceability information about batteries.

In the US, used batteries are generally considered hazardous or universal waste, which are then bound to existing waste regulations.

European Union

The European Union has introduced a regulation aimed to increase EOL management of EV batteries and provisions for digital records of batteries.

China

In China, the government established a traceability management platform to track electric vehicle batteries throughout their lifetime in 2018.[10]

The government released a set of policies that place this responsibility on EV and battery manufacturers or importers. Vehicle manufacturers are required to provide technical support to these enterprises and are responsible for selling batteries to a qualified handler for reuse or recycling. A unique code is attached to every battery produced in or imported into China for use in EVs to allow for tracking and proper processing at the end of the battery's first life.[11]

Vehicle manufacturers are required to provide technical support to these enterprises and are responsible for selling batteries to a qualified handler for reuse or recycling.

[8]"Pathways to Achieve New Circular Vision for Lithium-Ion Batteries." n.d. NREL. https://www.nrel.gov/news/program/2021/pathways-to-achieve-new-circular-vision-for-lithium-ion-batteries.html.

[9]US EPA, OLEM. 2015. "Resource Conservation and Recovery Act (RCRA) Regulations." US EPA. August 18, 2015. https://www.epa.gov/rcra/resource-conservation-and-recovery-act-rcra-regulations.

[10]"China Launches Pilot EV Battery Recycling Schemes," Reuters, July 26, 2018, sec. Environment. Reuters. https://www.reuters.com/article/us-china-autos-batteries/china-launches-pilot-ev-battery-recycling-schemes-idUSKBN1KF375.

[11]Ambrose. H., O'Dea, J. (2021). Electric Vehicle Batteries: Addressing Questions about Critical Materials and Recycling. February 11, 2021, Union of Concerned Scientists. https://www.ucsusa.org/resources.

PARTIES RESPONSIBLE FOR INFORMATION MANAGEMENT

Regulation proposals like those listed above have introduced requirements to designate responsible parties for handling matters related to EV battery EOL management.

Regulation proposals and policymaking efforts like those listed above have introduced requirements for stakeholders to designate responsible parties for handling matters related to EV battery EOL management. Additionally, due to the battery passport requirements included in the EU Battery Regulation, stakeholders operating in the EU will be tasked with the responsibility of managing comprehensive information about battery packs, materials, components, and related data.

The following list provides a summary of responsible parties in EV battery EOL management and the information they typically provide to their trading partners.

Battery Manufacturers

Battery manufacturers assemble and produce battery packs for EV Manufacturers (OEMs). They may also be involved in cathode and cell manufacture. Each pack contains cells assembled into modules along with the battery management system. Pack assembly is sometimes done by the OEM.

Information Provided to Trading Partners: Battery Manufacturers are responsible for providing the battery's bill of materials information to OEMs. They may register the materials used in the batteries through open platforms. They label the individual packs with serial numbers, global unique identity, safety information, etc. They ship the packs, which means they must provide information about the battery content to the transportation company.

Information Received from Trading Partners: Battery Manufacturers receive information from cell manufacturers and material sourcing companies about chemical compositions, ethical sourcing, and recycled material contents.

EV Manufacturers (OEMs)

EV Manufacturers produce EVs and install battery packs to vehicles in the assembly, during which a battery pack with an identity is assigned to the vehicle and the VIN.

EV Manufacturers produce EVs and install battery packs to vehicles in the assembly, during which a battery pack with an identity (serial number provided by the Battery Manufacturer) is assigned to the vehicle and the vehicle identification number (VIN).

Information Provided to Trading Partners: As per the EU battery regulations, since OEMs are the ones responsible for "putting the battery to a market," they will be held accountable for the information's traceability and auditability.

Information Received from Trading Partners: OEMs rely on information about battery composition and sourcing information provided to them by the pack manufacturers and other suppliers.

Collection, Dismantling, and Sorting Companies

The tasks of collection and sorting may be distributed among different companies in some cases and require proper training for safe handling and storage of used batteries.

Collection and Sorting Companies gather used batteries from designated locations and safely store them in warehouses. The tasks of collection and sorting may be distributed among different companies in some cases and require proper training for safe handling and storage of used batteries. These companies supply used batteries to other companies involved in battery recycling/repurposing/reuse.

Information Provided to Trading Partners: Collection, Dismantling, and Sorting Companies can provide information about which packs they received/sorted were sent to which EOL company. However, they may argue that such information is confidential and hence cannot be made public.

Battery Recycling Companies

Battery Recycling Companies recycle material from used batteries through various mechanisms.

Battery Recycling Companies recycle material from used batteries through various mechanisms, such as pyrometallurgical and hydrometallurgical processes, and extract critical minerals.

Information Provided to Trading Partners: Some recycling companies already maintain a list of battery serial numbers that they recycle and provide a list back to the manufacturers or OEMs as proof of recycling.

Battery Repurposing Companies

Battery Repurposing Companies repurpose used battery packs and/or modules for secondary purposes such as grid storage, and utility backups.

Battery Repurposing Companies repurpose used battery packs and/or modules for secondary purposes such as grid storage, and utility backups. They may remove modules/cells from the original pack and reform them into a different pack for second use such as grid storage. They may assign a different serial number for the new pack. However, they need to maintain a record of deprecation of the old serial number.

Battery Swapping/Reuse Companies

Battery Swapping/Reuse Companies allow consumers to swap an old battery with a new one. This use case has not gained much traction in large-form batteries but has gained popularity for smaller batteries used in two-wheelers. They may remove/repair modules/cells and put them back into the original pack. They may have to update the battery composition but keep the same serial number for the new pack.

Battery Testing Companies

Battery Testing Companies provide battery testing and certification services, ensuring energy storage technologies meet performance, reliability, and safety criteria.

Battery Testing Companies provide battery testing and certification services, ensuring energy storage technologies meet performance, reliability, and safety criteria. Information Provided to Trading Partners: Battery Testing Companies perform tests on cells and modules to determine SOH and SOC on behalf of repurposing/reuse companies and provide the certificate of test to the regulators.

Transport Companies

Transport Companies serve manufacturers and distributors to physically transport and store minerals, manufactured components, and battery packs.

Information Provided to Trading Partners: Provide information about the risks of transporting used and waste batteries to local/national environmental regulators and insurance companies.

Government Regulators & Policymakers

Government Regulators and Policymakers propose and enforce local and national level regulations concerning battery recycling to meet sustainability goals.

Government Regulators and Policymakers propose and enforce local and national level regulations concerning battery recycling to meet sustainability goals. For these stakeholders, traceability of the battery's critical minerals is important to align with the goals and long-term economic policies on reducing reliance on mineral import.

Information Received: Verify claims of battery traceability provided by the pack manufacturers, OEMs, and repurposing/reuse companies.

EV Dealers and Repair Shops

EV Dealers and Repair Shops receive requests from vehicle and fleet owners to check and repair EV batteries.

EV Dealers and Repair Shops receive requests from vehicle and fleet owners to check and repair EV batteries. They may be involved in finding issues in the battery pack. Dealers and repair shops are not quite qualified to perform module-level repairs.

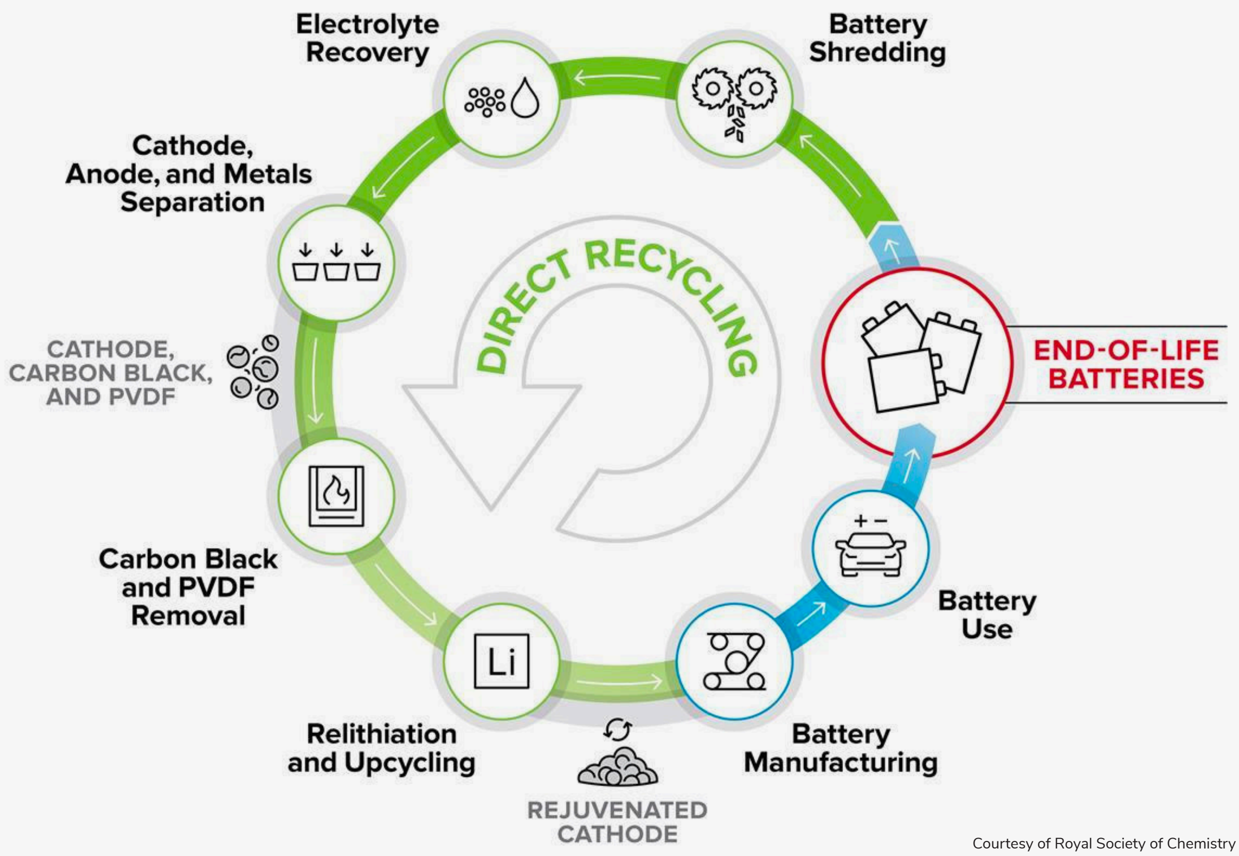
Information Provided to Trading Partners: A dealer or repair shop may report their findings to the OEM, which may ask the dealer or repair shop to ship the faulty battery/module to it or the battery manufacturer.

EV Owners & EV Fleet/ Rental Companies

As end-consumers, EV Owners and EV Fleet/ Rental Companies monitor the performance of EV batteries during regular usage.

As end-consumers, EV Owners and EV Fleet/Rental Companies monitor the performance of EV batteries during regular usage. They need to know the state of batteries (new and old) to make vehicle buying/selling decisions. They may inform the vehicle manufacturers that may ask the dealers to ship the faulty battery/module to it or the battery manufacturer.

Courtesy of The Globe and Mail



Courtesy of Royal Society of Chemistry

COLLECTION, STORAGE, AND TRANSPORT

It can be challenging to collect batteries that have reached EOL due to the multiplicity of possible ways that a vehicle/ battery can be returned or retired.

Collection and Sorting

The entities collecting used batteries need information on the condition of individual batteries. This is especially critical to identify batteries with potential thermal events. It can be challenging to collect batteries that have reached EOL due to the multiplicity of possible ways that a vehicle/battery can be returned or retired. Vehicles or batteries may be returned/retired in a dealership and OEM network or outside such a network. There is uncertainty regarding returning/ retiring EVs that are out of warranty and it is difficult to track what happens to out-of-warranty batteries at EOL. [12]

Depending on the batteries' SOH and condition, eligible batteries are designated for second-life use or for recycling. LiBs are produced by a variety of manufacturers employing different chemistries; recyclers and repurposing companies often do not know a given battery's chemistry, capacity, or SOH.

[12]Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. "Lithium-Ion Car Battery Recycling Advisory Group Final Report." CalEPA. 16 March, 2022, CalEPA. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf.

A standardized and more accurate method of battery SOH reporting can potentially help in addressing whether a given battery is used or whether it qualifies as waste to be recycled.

A standardized, reliable, and more accurate method of battery SOH reporting can potentially help in addressing whether a given battery is used or whether it qualifies as waste to be recycled after the sorting process. Hence, the sorting company may be a defining entity that separates used vs. waste batteries based on SOH/temperature/physical deformities and sends the batteries to pertinent recyclers or repurposing/reusing companies.

Information on a battery's history and SOH at the collection stage is important to determine whether the battery should be recycled, reused, or repurposed.[13] Knowing this information beforehand can help responsible entities streamline the EOL management process and ensure safety in battery handling. Information on battery chemistry is crucial for recyclers to increase the efficiency of the material recovery process and determine how a given battery should be handled. Lastly, information on safe handling should be made readily available in training materials by the battery manufacturers.

Storage and Transport

Prior to reuse, repurposing, or recycling, batteries may first need to be stored at a facility before shipping/transporting in bulk to make transportation more cost-effective.

Storage companies, including scrap yards, store used/waste batteries gathered by the collection companies. Storage may happen at different stages of the used battery's life cycle. Prior to reuse, repurposing, or recycling, batteries may first need to be stored at a facility before shipping/transporting in bulk to make transportation more cost-effective.[14] There is a complex network of companies involved in the storage and logistics process of used batteries.

Safety is one of the most important aspects that impacts how used batteries are stored and transported. EV batteries pose a significant electrocution risk when handled incorrectly and the risk is higher for physically damaged batteries.[15] EV batteries also pose a significant fire risk in storage and transportation. Facilities where EV batteries are stored and dismantled must take safety precautions, including proper staff training and equipment.

A used EV battery may end up in unlicensed dismantlers where capturing into the recycling, reuse, and repurposing cycle becomes very difficult.

Ownership of vehicles that have reached EOL due to collision is usually transferred to insurance companies, which are likely to sell the vehicles at insurance auctions. Whereas vehicles with minimal value are sent to scrapyards (which are then responsible for sending batteries to a sorting, repurposing, or recycling facility). A used EV battery may end up in unlicensed dismantlers where capturing into the recycling, reuse, and repurposing cycle becomes very difficult.

[13] Sarmah, Sudipta Bijoy, Pankaj Kalita, Akhil Garg, Xiao-dong Niu, Xing-Wei Zhang, Xiongbin Peng, and Dipanwita Bhattacharjee. 2019. "A Review of State of Health Estimation of Energy Storage Systems: Challenges and Possible Solutions for Futuristic Applications of Li-Ion Battery Packs in Electric Vehicles." Journal of Electrochemical Energy Conversion and Storage 16 (4): 040801. https://doi.org/10.1115/1.4042987.

[14] Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. "Lithium-Ion Car Battery Recycling Advisory Group Final Report." CalEPA. 16 March, 2022, CalEPA. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf.

[15] Bisschop, Roeland, Ola Willstrand, and Max Rosengren. 2020. "Handling Lithium-Ion Batteries in Electric Vehicles: Preventing and Recovering from Hazardous Events." Fire Technology 56 (6): 2671–94. https://doi.org/10.1007/s10694-020-01038-1.

Transportation of used/waste batteries is a crucial link that binds collection to storage to further recycling/repurposing. It is also one of the costliest stages in EOL management. These high costs associated with transport generally stem from multiple factors, insurance rates for transporting hazardous materials being one of the biggest drivers.

Information Sharing Gaps

Collections companies typically do not know the manufacturer, composition, or internal state of batteries before collecting them from various sources. Sorting or storage companies can create records of batteries received using the serial numbers from the battery labels.

Collections companies typically do not know the manufacturer, composition, or internal state of batteries before collecting them from various sources (such as automotive dealers, individuals, etc.) Their primary responsibility is to gather the used/waste batteries and bring them to a sorting company location. Hence, collections companies cannot provide reliable battery information to sorting companies.

Sorting companies are charged with segregating batteries based on manufacturer, weight, type, etc. The sorting may also happen at the storage facility, where batteries are separated into different bins. The sorting or storage companies can create records of batteries received using the serial numbers from the battery labels. In most cases, sorting and storage companies do not report such information to storage facilities, transport companies, disassemblers, or recyclers. Transport companies also may not know the state of the batteries they are moving.

REUSE AND REPURPOSING OF USED BATTERIES

Definitions

Used batteries that are not waste and have remaining capacity in terms of performance can be either repurposed or reused.

Used batteries that are not waste and have remaining capacity in terms of performance can be either repurposed or reused. If there is enough SOH and there is no physical damage or potential for thermal events, then a battery can be repurposed for different uses such as in a stationary energy storage system. In reuse, the battery will be repaired by replacing damaged cells/modules or other hardware components and putting them back into the original battery pack. The image below shows a simple flowchart of how a battery is deemed fit for repurpose or reuse.

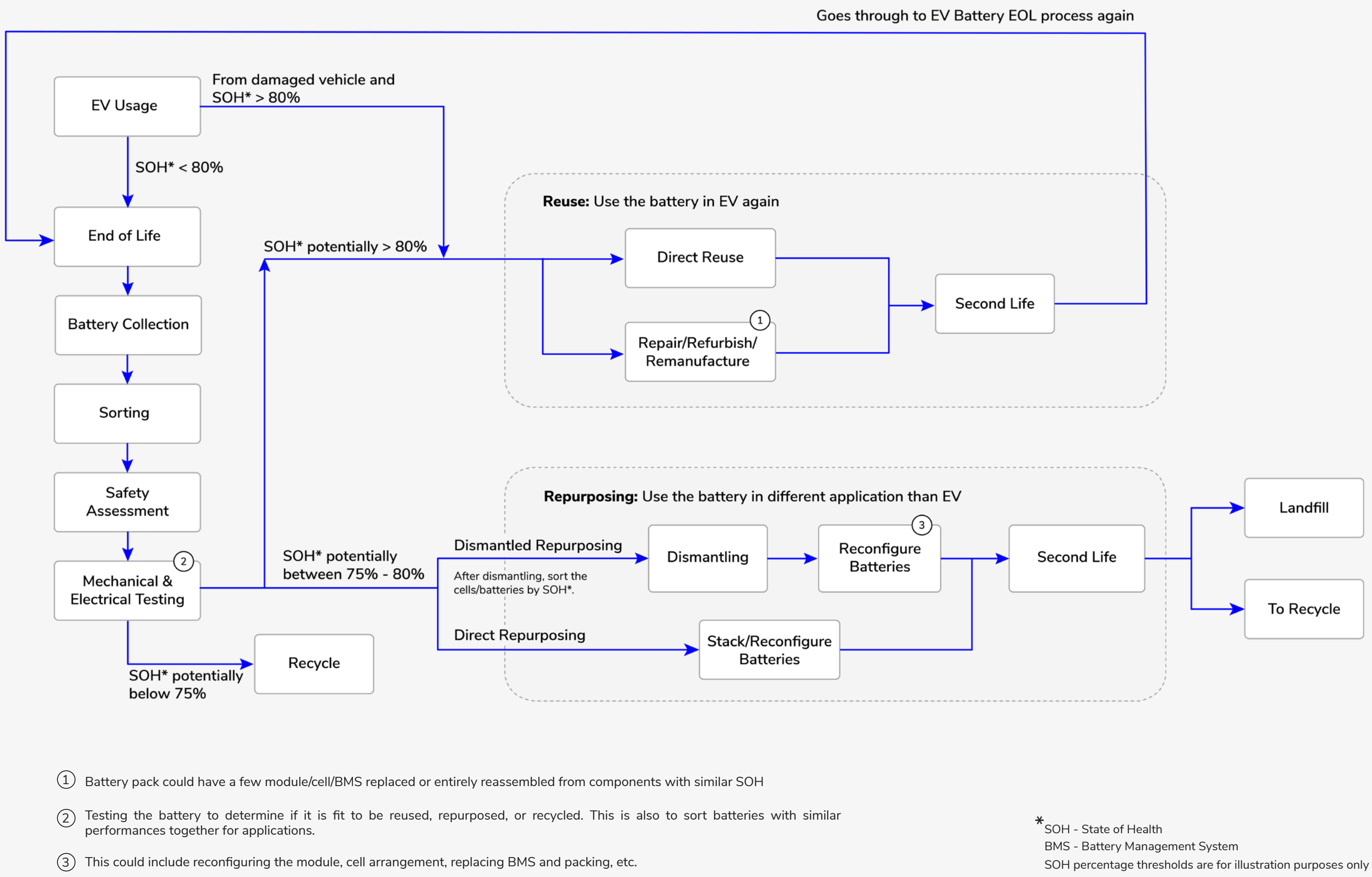


Figure 1. Workflow depicting how a battery is deemed fit for repurpose or reuse.

According to the EU Battery Regulation:

Repurposing means "any operation that results in parts or the complete battery that is not a waste battery"

Repurposing means "any operation that results in parts or the complete battery that is not a waste battery, being used for a different purpose or application than the one that the battery was originally designed for."

Remanufacturing means any technical operation on a used battery that includes the disassembly of all its battery modules and cells and the use of a certain amount.

Remanufacturing means "any technical operation on a used battery that includes the disassembly and evaluation of all its battery modules and cells and the use of a certain amount of battery cells and modules, new, used or recovered from waste, or other battery components, to restore the battery capacity to at least 90% of the original rated battery capacity, and where the state of health of all individual battery cells is homogeneous, not differing more than 3% from one another, and results in the battery being used for the same purpose or application than the one for which the battery was originally designed."

State of the Practice

There are three main steps involved in EV battery repurposing: [16]

- Testing cells for performance,
- Removing packs and cells, and
- Reconfiguring for second-life applications.

These metrics will determine suitable second-life use cases for a given battery or group of batteries

Testing gauges the performance metrics of the battery, like the SOH, cell temperature. These metrics will determine suitable second-life use cases for a given battery or group of batteries. The closer the match, the better the restored battery will perform. There are two broad categories of SOH estimation methods for EV LiBs:[17]

Experimental methods
(1) directly measure capacity by discharging and charging and
(2) measure certain proxy parameters, such as impedance and internal resistance, using laboratory devices such as spectroscopy.

Model-based methods are based on physical equations and curve fitting, machine learning algorithms.

There are also hybrid methods, which combine experimental and model-based methods.

EV batteries are also usually high voltage and require safety training.

Removing the battery packs and battery cells. This can be challenging for various reasons. Many current batteries are not designed to be taken apart and the OEMs have been designing the battery with different form factors and chemistry. EV batteries are also usually high voltage and require safety training.

Stationary storage batteries can be used in a wide range of use cases like load sharing, backup power supply, and storing green photo-voltaic system energy.

Reconfiguring the packs for second-life applications such as stationary storage. More specially, stationary storage batteries can be used in a wide range of residential, commercial, and industrial use cases like load sharing, backup power supply, and storing green photo-voltaic system energy. Batteries can be also used as backup power systems in residential or commercial buildings. Since renewable energies are by nature intermittent, being able to store energy is critical to support their expansion and ultimately decrease the carbon footprint of the energy sector.

Many projects and experiments have been tested around the world from pilot to commercial facilities.

- General Motors partnered with residential energy providers to test the cost efficiencies and utility of the system using Chevy Volt LiBs[18].

[16]"Battery Reuse: A Second-Life for Electric Vehicle Batteries Background Information for the California Lithium Battery Recycling Advisory Group." May 27, 2020, CalEPA. https://calepa.ca.gov/wp-content/uploads/sites/6/2020/07/Lithium-ion-Work-Group-Ambrose_LIB-AG-Meeting-Materials-5-27-20_a.hp_.pdf.

[17]Noura, Nassim, Loïc Boulon, and Samir Jemeï. "A Review of Battery State of Health Estimation Methods: Hybrid Electric Vehicle Challenges." World Electric Vehicle Journal 11, no. 4 (2020): 66. https://doi.org/10.3390/wevj11040066.

[18]Zhao, Yanyan, Oliver Pohl, Anand I. Bhatt, Gavin E. Collis, Peter J. Mahon, Thomas Rüther, and Anthony F. Hollenkamp. "A Review on Battery Market Trends, Second-Life Reuse, and Recycling." Sustainable Chemistry 2, no. 1 (2021): 167–205. https://doi.org/10.3390/suschem2010011.

» Toyota is planning to use retired batteries to power 7-Eleven stores in Japan. Toyota donated 208 hybrid battery packs with solar arrays to Yellowstone National Park's Ranger Station and Education Center to provide sustainable power[19].

» Daimler launched projects for stationary energy storage also. Their Netherlands site has built a 2.8MWh system in 2018. Their recycling plant in Lunen has a 13MWh storage system.

» In California, B2U storage solution built an 8MWh system connected to PV system and is expanding to 17MWh[20].

A cost-benefit analysis was done independently for each of the three types of post-vehicle-application processing by the Mineta National Transit Research Consortium. Among the three types of processing, repurposing is a less well-defined application area that is profitable if the development cost is at most USD 83/kWh to USD 114/kWh, depending on research and development expenses.[21]

Neubauer et al. found that repurposing costs can be as low as USD 20/kWh if vehicle diagnostics data are available to support used battery purchases.

Neubauer et al. found that repurposing costs can be as low as USD 20/kWh if vehicle diagnostics data are available to support used battery purchases. It is economically impractical to replace faulty cells within modules, therefore minimizing purchases of modules containing faulty cells is critical[22]. As predicted by Mineta National Transit Research Consortium, available post-vehicle application batteries could range from 1.376 million to 6.759 million — an ample supply for repurposing[23].

High-performance applications for electric vehicles (EVs) typically demand an initial capacity retention of 80% or higher.

High-performance applications for electric vehicles (EVs) typically demand an initial capacity retention of 80% or higher, indicating that the batteries still retain a substantial portion of their original capacity and value. Given the abundance of available supply, the efficient utilization of the residual value present in these costly battery components assumes critical economic significance. Furthermore, from an environmental perspective, ensuring the safe handling of materials, particularly heavy metals like Nickel and Cobalt, is imperative due to their toxic nature. Second-life application of batteries also serves as a viable alternative to direct battery recycling, affording the industry more time to enhance existing recycling techniques. It is estimated that batteries can be extended by at least 10 years, or potentially even longer, contingent upon the specific applications in which they are employed[24].

[19]Standridge, Charles R., and Lindsay Corneal,. Rep. REMANUFACTURING, REPURPOSING, AND RECYCLING OF POST-VEHICLE-APPLICATION LITHIUM-ION BATTERIES. Mineta National Transit Research Consortium, June 2014. https://transweb.sjsu.edu/sites/default/files/1137-post-vehicle-Li-Ion-recycling.pdf.

[20,24]Ambrose, Hanjiro. "Lithium-Ion Car Battery Recycling Group Meeting Minutes May 27, 2020." https://calepa.ca.gov/wp-content/uploads/sites/6/2020/07/Lithium-ion-Work-Group-Ambrose_LIB-AG-Meeting-Materials-5-27-20_a.hp_.pdf. Accessed May 14, 2023.

[21]Standridge, Charles R., and Lindsay Corneal,. Rep. REMANUFACTURING, REPURPOSING, AND RECYCLING OF POST-VEHICLE-APPLICATION LITHIUM-ION BATTERIES. Mineta National Transit Research Consortium, June 2014. https://transweb.sjsu.edu/sites/default/files/1137-post-vehicle-Li-Ion-recycling.pdf.

[22]Neubauer, J., E. Wood, and A. Pesaran. Rep. Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries. National Renewable Energy Laboratory, February 2015. https://www.nrel.gov/docs/fy15osti/63332.pdf.

[23]Standridge, Charles R., and Lindsay Corneal,. Rep. REMANUFACTURING, REPURPOSING, AND RECYCLING OF POST-VEHICLE-APPLICATION LITHIUM-ION BATTERIES. Mineta National Transit Research Consortium, June 2014. https://transweb.sjsu.edu/sites/default/files/1137-post-vehicle-Li-Ion-recycling.pdf.

Information Sharing Gaps

Batteries usually arrive at third-party reuse centers as enigmatic "black boxes," making it challenging to access the essential information required to optimize reuse practices.

Batteries usually arrive at third-party reuse centers as enigmatic "black boxes," making it challenging to access[25] the essential information required to optimize reuse practices. In the context of information needed by reuse and repurposing companies, they often encounter difficulties in obtaining readily accessible data about battery design, chemistry, SOH, and usage history. These obstacles frequently necessitate expensive testing procedures and limit their capacity to fine-tune the reuse processes.

Adding to the complexity, battery manufacturers are continuously engaged in innovating their battery technologies to maintain competitiveness.

Adding to the complexity, battery manufacturers are continuously engaged in innovating their battery technologies to maintain competitiveness. This constant innovation contributes to the extensive diversity seen in battery configurations, encompassing aspects such as design, shape, size, mass, and chemistry. This diversity is a defining characteristic of the contemporary EV market.

For repurposing, although the companies are not required to maintain the linkages, the EU Battery Regulation requires such linkage to be maintained in the battery passport system.

In order to maintain linkage between the first use and later use of the same battery in the case of reuse, the reusing company has to maintain in its system such identity linkage along with battery composition updates. For repurposing, although the companies are not required to maintain the linkages, the EU Battery Regulation requires such linkage to be maintained in the battery passport system.

RECYCLING OF WASTE BATTERIES

Definition

Recycling of EV batteries involves the extraction of materials from waste batteries.

Recycling of EV batteries involves the extraction of materials from waste batteries. At present, recycling is the most viable option for an EOL battery that can't be reused or repurposed due to quality and safety requirements, economic feasibility, and geographic limitations (such as the lack of facilities or transport infrastructure needed.)

State of the Practice

Soon-to-be enacted regulations and other policy-making efforts around the globe are pushing battery manufacturers and automakers to use and/or produce more environmentally sustainable batteries.

Although the LiB recycling market is still in the early phases, it has massive potential for growth as recycling can aid the critical material shortage or procurement issues that many battery manufacturers are facing today. Additionally, soon-to-be enacted regulations and other policy-making efforts around the globe are pushing battery manufacturers and automakers to use and/or produce more environmentally sustainable batteries. The most common methods of recycling today are hydrometallurgical and pyrometallurgical methods. These can be done separately or in combination[26].

[25]Tankou, A., Bieker, G., Hall, D., "SCALING UP REUSE AND RECYCLING OF ELECTRIC VEHICLE BATTERIES: ASSESSING CHALLENGES AND POLICY APPROACHES - WHITE PAPER," February 2023, https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf

[26]Chengetai Portia Makwarimba, Minghui Tang, Yaqi Peng, Shengyong Lu, Lingxia Zheng, Zhefei Zhao, Ai-gang Zhen, Assessment of recycling methods and processes for lithium-ion batteries,iScience, Volume 25, Issue 5, 2022, 104321, ISSN 2589-0042, https://doi.org/10.1016/j.isci.2022.104321.

Most recycling companies collaborate with recycling organizations or a recycling program to ensure sufficient recycling amounts and that certain guidelines or rules are met.

Initially, a mechanical treatment takes place after the EOL batteries are sorted and labeled for recycling. Most recycling companies collaborate with recycling organizations or a recycling program to ensure sufficient recycling amounts and that certain guidelines or rules are met.

Meanwhile, some recyclers will only recycle until the "black mass" is obtained, at which point they will sell the black mass to other recyclers for further processing. Black mass is made up of metal oxides in the battery and carbon. More than half of the world's recycling facilities are based in the US[27]. They are trying to tackle challenges with LiB recycling and commercializing new technologies for recovering Lithium, Cobalt, and Nickel from spent batteries.

Closed-Loop Recycling

Closed-loop recycling is needed to achieve long-term supply chain viability and sustainability

In a closed-loop recycling system, all of the materials used in a product or goods can ideally be recycled, and recovered materials can go into the manufacturing of the same type of product again. Closed-loop recycling is needed to achieve long-term supply chain viability and sustainability. Usually, products that can be recycled in a closed loop or near closed-loop system are designed such that they can be easily recycled and materials can be recovered with high efficiency or higher purity. For example, aluminum can recycling is considered closed-loop recycling as the aluminum can go back into making more aluminum cans.

LiBs can be recycled in a closed-loop system via direct recycling, where many critical materials can be recovered.

LiBs can be recycled in a closed-loop system via direct recycling, where many critical materials can be recovered. Although the process is still not ideal today, there are direct recycling technologies with relatively high recovery rates. With the ongoing development and innovation in this field, it is plausible to assume that direct recycling systems will increase the efficiency of closed-loop LiB recycling in the future[28].

Open Loop Recycling

Open-loop recycling is also referred to as downcycling or reprocessing. Today, open-loop recycling is more common in LiB recycling.

In an open loop recycling system, products or goods with similar compositions can be recycled together or separately and the quality of recovered materials is generally altered through heat, chemical reactions, or physical crushing. The key difference is that the recovered materials usually go back into the manufacturing process of a different product (with lower-quality material requirements). Open-loop recycling is also referred to[29] as downcycling or reprocessing. Today, open-loop recycling is more common in LiB recycling. With ongoing regulatory efforts to increase the rate of recycling and increasingly stringent guidelines on recovery rates and quality, it is expected that open-loop recycling systems will be improved and the industry as a whole will move towards closed-loop recycling.

[27]IEA. 2023. "Global EV Outlook 2023 Catching up with Climate Ambitions." https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf.

[28]"What's the Difference between Open-Loop and Closed-Loop Recycling?" November 19, 2021, The Pro Design Group. https://theprodesigngroup.com/whats-the-difference-between-open-loop-and-closed-loop-recycling/.

[29]"Open-Loop vs Closed-Loop Recycling." 2018. General Kinematics. March 27, 2018. https://www.generalkinematics.com/blog/open-loop-vs-closed-loop-recycling/.

Recycling Methods

Treatment

Treatment processes include mechanical and thermal processes to prepare the battery for recycling.

Treatment processes include mechanical and thermal processes to prepare the battery for recycling. Depending on the battery and the recycling process, different steps may be applied. This subsection reviews some of the most common methods. Generally, the first step in treatment is discharging and deactivating the battery to ensure safety.[30] Pyrolysis (high-temperature treatment allowing the organic compounds to thermally decompose while the CAM is maintained as solid residue) is an alternative method that can be used to deactivate the battery. After the battery has been deactivated, it may undergo dismantling/disassembly, which involves removing various components of the battery such as casing reducing the battery to modules or cells.

Batteries may be mechanically shredded once packs have been discharged and dismantled/disassembled.

Batteries may be mechanically shredded once packs have been discharged and dismantled/disassembled. Air classification, sieving, and magnetic separation are applied after shredding to sort the components of the shredded battery. The shredded materials are sorted into metal-enriched liquid, plastic fluff, and metal solids. These are then further sorted to obtain black mass. Most of the aluminum, copper, and/or steel casings are recovered at this step. The black mass contains relatively high concentrations of Nickel, Cobalt, Lithium, and Manganese.[31] These materials can be recovered from black mass via a pyrometallurgical process followed by a hydrometallurgical process, or directly through hydrometallurgical processes.

Depending on the degree of mechanical processing, the amount and quality of recovered materials vary (more complex treatment can yield a higher quality/ amount output.)

Pyrometallurgical Recycling

In pyrometallurgical recycling, LiB modules are smelted in a high-temperature furnace to make a concentrated metallic alloy.

In pyrometallurgical recycling, LiB modules are smelted in a high-temperature furnace to make a concentrated metallic alloy. This alloy consists of nickel, copper, and cobalt, which then can be further extracted through a hydrometallurgical recycling process. Lithium, manganese, and graphite are lost into the slag (depending on the battery composition). Lithium and manganese can be extracted and recovered from the slag through a hydrometallurgical process.[32] Alternatively, the slag may be directly used in the construction industry. Pyrometallurgical processes can achieve high recovery yields for cobalt, nickel, and copper.[33]

[30]"Battery Carbon Footprint Rules for calculating the Carbon Footprint of the 'Distribution' and 'End-of-life and recycling' life cycle stages" April 2023, Battery Pass. https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Carbon_Footprint_Rules.pdf.

[31]Brunn, Michael. 2021. "Black Mass One of the Hottest Issues in Battery Recycling." RECYCLING Magazine. September 10, 2021. https://www.recycling-magazine.com/2021/09/10/black-mass-one-of-the-hottest-issues-in-battery-recycling/ .

[32]REN, Guo-xing, Cai-bin LIAO, Zhi-hong LIU, and Song-wen XIAO. 2022. "Lithium and Manganese Extraction from Manganese-Rich Slag Originated from Pyrometallurgy of Spent Lithium-Ion Battery." Transactions of Nonferrous Metals Society of China 32 (8): 2746–56. https://doi.org/10.1016/s1003-6326(22)65981-8.

[33]"Battery Recycling Takes the Driver's Seat." March 13, 2023, McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-recycling-takes-the-drivers-seat.

Hydrometallurgical Recycling

In hydrometallurgical recycling, impurities of the black mass are removed through a chemical process called leaching and separation.

In hydrometallurgical recycling, impurities of the black mass are removed through a chemical process called leaching. The process flows of hydrometallurgical processes vary; however, they generally include leaching, purification/separation, precipitation, and crystallization or electrowinning.[34] Leaching involves dissolving the metals in the black mass via a leaching media. In purification/separation, metals are separated and purified via chemical reactions. Then, metals are recovered from the solution through crystallization or ionic precipitation. To further increase the purity of lithium, nickel, manganese, and cobalt, solvent extraction can be applied.

Direct Recycling

Direct recycling generally involves a combination of pyrometallurgical and hydrometallurgical processes.

Direct recycling generally involves a combination of pyrometallurgical and hydrometallurgical processes.[35] In this process, cathode materials are recovered, which then can be directly used in battery production, without having to be broken down into individual materials.[36] Relatively, direct recycling offers substantial advantages environmentally, economically and in terms of safety. There aren't many commercially deployed direct recycling technologies yet but it is a promising solution to battery supply chain problems as the most expensive and important component of the battery can be recovered and go into the manufacturing of new LiBs.

Information Sharing Gaps

The recyclers then take possession of the batteries and, if requested, provide proof of recycling to the OEMs.

Recycling companies typically know the origin of the waste batteries as they arrive from sorting and storage facilities as well as directly from the OEMs or battery manufacturers. The recyclers then take possession of the batteries and, if requested, provide proof of recycling to the OEMs. Recyclers can provide proof of recycling certificates to their customers on a batch basis rather than an individual battery basis, and must coordinate with their customers to provide such certificates on an individual basis. This is still challenging for recyclers, since they may extract minerals in batches that may include packs from different OEMs or battery manufacturers.

[34]Battery Pass. "Battery Carbon Footprint Rules for calculating the Carbon Footprint of the 'Distribution' and 'End-of-life and recycling' life cycle stages" April 2023. https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Carbon_Footprint_Rules.pdf.

[35]Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. "Lithium-Ion Car Battery Recycling Advisory Group Final Report." CalEPA. 16 March, 2022, CalEPA. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf.

[36]Wei, Gaolei, Yuxuan Liu, Binglei Jiao, Nana Chang, Mengting Wu, Gangfeng Liu, Xiao Lin, et al. 2023. "Direct Recycling of Spent Li-Ion Batteries: Challenges and Opportunities toward Practical Applications." IScience 26 (9): 107676. https://doi.org/10.1016/j.isci.2023.107676.

PROPOSED REGULATIONS

Various proposed regulations described below will require information sharing about batteries between the supply chain members, regulators, and end-users.

Various proposed regulations described below will require information sharing about batteries between the supply chain members, regulators, and end-users at an unprecedented level throughout the life of batteries. The following sections summarize, at a high level, such information sharing requirements.

European Union Battery Regulations

The regulation also requires labeling on automotive and industrial batteries to indicate material content, quantity, and origin.

The revised EU Battery Regulation addresses many aspects of the LiB lifecycle. Critically, this regulation requires OEMs to provide open access to information about batteries with a capacity of 2 kWh or more[37] to facilitate the handling of batteries and determine EOL application. The regulation also requires labeling on automotive and industrial batteries to indicate material content, quantity, and origin.

» Starting in 2027, batteries produced in the EU shall be labeled with the manufacturer name, battery type, date of manufacture, presence of hazardous substances, and other information that facilitates recycling or reuse.

» Documentation or certificate on change of ownership, technical aspects, and status shall be required for repurposed and reused batteries.

» EOL information shall be included by battery manufacturers to minimize waste and contribute to the reuse and recycling.

» Information on how batteries should be safely dismantled, transported and recycled is also attached in a safety label on the batteries.

» Manufacturers shall be required to disclose the environmental impact of batteries they produce.

The regulation mandates increased recycling and reuse, setting rules for extended producer responsibility and requiring stakeholders to annually report on batteries recycled and material recycling rates.

Increased recycling and reuse is another key element in the regulation. The regulation defines general rules for extended producer responsibility and the roles of relevant stakeholders/parties (such as producer responsibility organizations). Producers, recyclers, and other parties (if any) defined under the extended producer responsibility scheme will be required to annually report on batteries handled/recycled and the recycling rates of the various materials.

Producers, recyclers, and other parties defined under the extended producer responsibility scheme will be required to annually report on batteries handled/recycled and the recycling rates.

Meanwhile, waste management operators and recyclers will be required to report to competent authorities for each year and Member State (where the batteries were collected): the number of waste batteries received for treatment; the number of waste batteries that began preparation for re-use; data on recycling efficiency for waste batteries; recovery of materials from waste batteries; and the destination and yield of the final output fractions. EU Member States are required to publicly disclose this data, as outlined in Article 76, in aggregated form annually, in the format established by the Commission.

[37] European Parliament legislative resolution of 12 July 2023 on the proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU), 12 July 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542.

Annex 12 defines recycling requirements and the deadlines for compliance/ effective dates of compliance. Regulation demands that recyclers achieve the recycling efficiency targets delineated in Part B and material recovery targets delineated in Part C. The first requirements are related to storage and treatment (before recycling) for EOL batteries to ensure safety and proper handling.

The recycling requirements increase to 80% by average weight for lead-acid batteries and to 80% by average weight for lithiumbased batteries by 31 December 2030.

According to the regulation, 65% by average weight of lithium-based batteries need to be recycled by 31 December 2025 (please refer to Annex 12 Part B of the EU Battery Directive for recycling targets for other types of batteries). The recycling requirements increase to 80% by average weight for lead-acid batteries and to 80% by average weight for lithium-based batteries by 31 December 2030.

This is followed by Part C, which defines the target recovery rates for materials. Recycling needs to achieve recovery rates of 90 % for cobalt; 90 % for copper; 90 % for lead; 50 % for lithium and 90 % for nickel by 31 December 2027. These recovery targets increased to 95 % for cobalt; 95 % for copper; 95 % for lead; 80 % for lithium and 95 % for nickel by 31 December 2031.

Lastly, used batteries can only be exported outside the EU if the recipient's battery management is compliant with EU requirements.

Meanwhile, producers will have to increase the collected number of portable batteries by 45% by 31 December 2023, 63% by December 2027, and 73% by December 2030. Lastly, used batteries can only be exported outside the EU if the recipient's battery management is compliant with EU requirements.

It is mentioned in the regulation that the targets for recycling efficiencies and material recovery in Annex 12 may be revised at least every five years according to market developments regarding the availability of minerals and technical and scientific development in battery/EOL technologies.

US Treasury Section 30D Tax Credits

The United States Department of Treasury published a notice of proposed rulemaking with regards to the Federal income tax credit under the Inflation Reduction Act of 2022 for the purchase of qualifying new clean vehicles, including new plug-in electric vehicles powered by an electric battery meeting certain requirements and new qualified fuel cell vehicles[38].

Depending on the year, the EV was put into service, the mineral requirement progressively increases from 40% to 80%.

"The critical minerals and battery components requirement with respect to the battery from which the electric motor of a vehicle draws electricity is satisfied if the percentage of the value of the applicable critical minerals contained in such battery that were (i) extracted or processed in the United States, or in any country with which the United States has a free trade agreement in effect, or (ii) recycled in North America, is equal to or greater than the applicable percentage (as certified by the qualified manufacturer, in such form or manner as prescribed by the Secretary)." Depending on the year, the EV was put into service, the mineral requirement progressively increases from 40% to 80%.

[38]DEPARTMENT OF THE TREASURY, 26 CFR Part 1, Section 30D New Clean Vehicle Credit, April 17, 2023, https://www.govinfo.gov/content/pkg/FR-2023-04-17/pdf/2023-06822.pdf.

The proposed guidance would provide the rules for determining compliance with the critical minerals requirement.

The proposed guidance would provide the rules for determining compliance with the critical minerals requirement, including a three-step process for determining the percentage of the value of the applicable critical minerals in a battery that contributes toward meeting the Critical Minerals Requirement. In Step 1, the manufacturer would need to determine the procurement chain or chains for each applicable critical mineral. In Step 2, each applicable critical mineral procurement chain in the battery would need to be evaluated to determine whether critical minerals procured from the chain have been (1) extracted or processed in the US, or in any country with which the United States has a free trade agreement in effect, or (2) recycled in North America. The third step would involve the calculation of the percentage of the value of qualifying critical minerals contained in a battery.

CalEPA Recycling Advisory Working Group

California Environmental Protection Agency (CalEPA) Lithium-Ion Car Battery Recycling Advisory Group published an extensive final report in 2022 regarding the recommended policies for handling batteries at EOL.

California Environmental Protection Agency (CalEPA) Lithium-Ion Car Battery Recycling Advisory Group published an extensive final report in 2022 regarding the recommended policies for handling batteries at EOL.[39] The advisory group, consisting of industry players, government agencies, and academic groups, identified two policies that garnered major support: core exchange with a vehicle backstop, and producer take-back. It should be noted that the recommended policies "complement, and do not replace, current warranty regulations and programs that require the vehicle manufacturer to properly reuse, repurpose, or recycle a removed EOL battery that is still under warranty."

Currently, there is no requirement for any party to coordinate and pay the collection, transportation, and EOL processing fees for out-of-warranty LiBs that have been retired. Whether a battery gets recycled, reused/repurposed, or sent to landfill is dependent on the economic value and feasibility, which results in stranded batteries.

There needs to be clearly defined responsibilities for EOL management and transfer of responsibility between responsible parties. The report also highlights the need to define what makes up proper recycling.

Thus, there needs to be clearly defined responsibilities for EOL management and transfer of responsibility between responsible parties. The report also highlights the need to define what makes up proper recycling. EOL responsibilities include battery re-labeling for identifying the responsible party in a reuse or repurposing scenario; setting up reverse logistics to transport batteries to recycling hubs; coverage of recycling costs; and documentation of recycling if necessary.

Based on existing policies for different vehicle parts and industry standards, this policy defines responsibility under three potential circumstances: recycling, reusing, and repurposing.

Core Exchange with a vehicle backstop policy gathered the highest support of 93% among the stakeholders polled for the report. Based on existing policies for different vehicle parts and industry standards, this policy defines responsibility under three potential circumstances: recycling, reusing, and repurposing.

» When a battery or any module or cell needs to be replaced before a vehicle reaches end-of-life, a core exchange program defined by the EV battery supplier shall be used. The party removing the battery shall make sure that it is reused, repurposed, or recycled properly. The party selling an EV battery shall track via a core exchange program whether the used battery has been managed accordingly.

[39] Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. "Lithium-Ion Car Battery Recycling Advisory Group Final Report." CalEPA. 16 March, 2022, CalEPA. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf.

- If a dismantler takes ownership of an EOL vehicle, then they shall be responsible for making sure that the battery is reused, repurposed, or recycled properly.
- Vehicle manufacturers shall be responsible for making sure that the vehicle is appropriately dismantled and the battery EOL is handled correctly if there is an EV reaching EOL where an OEM-certified battery is not acquired and removed by a licensed dismantler.

Producer take-back policy gathered the second highest rate of support (67%). In this policy, the responsibility to make sure that the battery is properly reused, repurposed, or recycled at a licensed facility (at zero cost to the consumer) belongs to the auto manufacturer when the battery is no longer needed by the owner and no other party has taken possession of the battery. The auto manufacturer is also responsible for providing educational materials to the service and repair entities as well as the customers. The responsibility of the auto manufacturer begins when they are informed that the battery can be handled and that it has reached EOL. The responsibility is transferred to a repurposer if the battery is repurposed.

The auto manufacturer is also responsible for providing educational materials to the service and repair entities as well as the customers.

Recommended policies focus on clearly defining responsibility in handling the end-of-life of EV batteries and mitigating the barriers that prevent EV batteries from being reused, repurposed, and recycled. The report points out that as EVs are not being retired in large volumes yet, these are nascent markets, hence policymaking needs to be iterative. Recommended policies also enable EOL EV batteries to be sold to a third party without the requirement of a partnership with the vehicle OEM, through which the battery can be reused or repurposed.

Recommended policies focus on clearly defining responsibility in handling the end-of-life of EV batteries and mitigating the barriers that prevent EV batteries from being reused, repurposed, and recycled.

Policies also incentivize the design of new EV batteries for easy disassembly and recycling. Both policies are promising solutions to address EOL management of out-of-warranty batteries. Disadvantages include potentially higher costs for battery and vehicle OEMs, which can be reflected onto customers as higher costs for EVs. This can also negatively impact EV adoption. In the event that a battery or vehicle OEM goes out of business, it could create a lack of responsible parties to manage the EOL of EV batteries and result in stranded batteries.

Policies also incentivize the design of new EV batteries for easy disassembly and recycling.

CLOSING THE INFORMATION GAPS

Standardizing Battery State Data Sharing

The regulation also requires SOH and other battery-related state data sharing between battery manufacturers, vehicle manufacturers, EOL management companies, end-users, and regulators.

The EU Roadmap on Raw Materials and Recycling points out the need for development of battery SOH diagnosis protocols to be used for sorting and classification of batteries at EOL for reuse, repurposing, or waste recycling[40]. The regulation also requires SOH and other battery-related state data sharing between battery manufacturers, vehicle manufacturers, EOL management companies, end-users, and regulators.

However, there are multiple challenges around sharing such data. Some of these challenges were identified from various pilot-scale battery recycling plants and second-life energy storage projects[41].

Although the SOH data can be made available using CANBus and OBD2 interfaces, there is no standardized way of reporting the SOH data to the EV battery supply chain.

For example, lengthy and costly processes are needed to determine battery SOH after the first life. Lithium-ion batteries are produced by a variety of manufacturers with different chemistries and algorithms (deemed proprietary) to estimate SOH. Although the SOH data can be made available using CANBus and OBD2 interfaces, there is no standardized way of reporting the SOH data to the EV battery supply chain.

A standardized, reliable, and more accurate way of SOH and other battery state data reporting can help in addressing these challenges.

Access to Battery State Data

Reuse and repurposing companies need access to information on the battery's SOH to estimate the remaining lifespan and determine whether the battery is suitable for a second-life application.

The parties involved in collecting/sorting/dismantling battery packs and modules need prompt information on the state of the battery, primarily SOH and temperature events. Reuse and repurposing companies need access to information on the battery's SOH to estimate the remaining lifespan and determine whether the battery is suitable for a second-life application[42]. By scanning the battery labels, these entities can access such information promptly at a large scale so that they can properly store and segregate used vs. waste batteries as well as safe vs. unsafe ones.

[40]European Commission, "ROADMAP on RAW MATERIALS and RECYCLING Prepared by Working Group 2." EU Roadmap on Raw Materials and Recycling

[41]Shell, Cassidy. 2021. "Battery Analytics and Diagnostics: How Big Data Makes EV Batteries Smarter, Increases Longevity and Unlocks Second-Life Use " January 25, 2021, Cleanteach Group. https://www.cleantech.com/battery-analytics-and-diagnostics-how-big-data-makes-ev-batteries-smarter-increases-longevity-and-unlocks-second-life-use/#:~:text=The%20intelligence%20generated%20by%20analytics .

[42]Sarmah, Sudipta Bijoy, Pankaj Kalita, Akhil Garg, Xiao-dong Niu, Xing-Wei Zhang, Xiongbin Peng, and Dipanwita Bhattacharjee. 2019. "A Review of State of Health Estimation of Energy Storage Systems: Challenges and Possible Solutions for Futuristic Applications of Li-Ion Battery Packs in Electric Vehicles." Journal of Electrochemical Energy Conversion and Storage 16 (4): 040801. https://doi.org/10.1115/1.4042987.

Using Data Source Verification

One of the critical requirements of proposed regulations (both EU and the US) is for the battery manufacturers, OEMs, and other responsible entities to be able to demonstrate that the digital battery data actually came from them. For the regulators to be able to easily verify such a source, the industry needs a system like a battery passport but also requires the responsible entities to digitally sign the data and preferably register such events in a tamper-evident ledger.

One of the critical requirements of proposed regulations is for the battery manufacturers, OEMs, and other responsible entities to be able to demonstrate that the digital battery data actually came from them.

Maintaining Persistent Battery Identity

The EU Battery Regulation also requires that a battery's unique identifier must be linked to any new identifiers created due to repurposing or reuse and such link should be persistent until the battery is recycled. For example, if an EV battery module is later repurposed as a home energy storage then the manufacturer of the storage battery has to ensure that the new unique identity it assigned is digitally linked to the previous identity of the battery manufactured by an OEM. This will require a common system by which the new manufacturer knows the unique identity of the battery, records such a link, and publishes the link for regulators and the general public.

The EU Battery Regulation also requires that a battery's unique identifier must be linked to any new identifiers created due to repurposing or reuse and such link should be persistent until the battery is recycled.

Use of Global Battery Passport

The role of global digital records of EV batteries and the need for a globally interoperable system for battery value chain members to access and manage such records is obvious. Article 65 of the EU battery regulation provides attributes that must be included in such digital records and also provides requirements for the implementation of a digital passport system.[43]

Article 65 of the EU battery regulation provides attributes that must be included in such digital records and also provides requirements for the implementation of a digital passport system.

We also believe if the value chain members are compliant with the EU regulation, it will facilitate compliance with the US Treasury's regulations on EV tax credits because the passport requirements of the EU are broadly scoped and the mineral traceability-related information can be used to assert compliance with the US Treasury's proposed regulation.

In order to facilitate the implementation of a global battery passport system, MOBI recently published a guideline on building a decentralized system that we believe will be compliant with the proposed EU and US Treasury regulations and meet their objectives of circularity and sustainability of EV batteries.

Courtesy of Princeton University

[43]European Parliament legislative resolution of 12 July 2023 on the proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU), 12 July 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542.

CONCLUSION

Closing information gaps in battery EOL management requires transparent, tamper-evident data sharing and standardized SOH reporting, supported by a persistent battery identity and global battery passports.

This white paper identifies the information gaps in end-to-end information sharing and traceability at the end of life phase of EV batteries. First, we present the current landscape including EOL pathways and processes involved in second life applications as well as information sharing in the EOL management of EV batteries. Then we discuss the regulatory landscape and various implications for information sharing at EOL. We identify the challenges and opportunities in ensuring transparent and compliant record keeping that come with the complexity of battery supply chains and lack of standards and frameworks.

We propose various strategies to close the information gaps in the supply chain including a standardized, reliable, and more accurate way of SOH reporting; enabling and facilitating access to battery data; using tamper-evident data source verification; maintaining persistent battery identity, and the use of global battery passports. We highlight that if implemented in a tamper-evident way, the battery passport presents a promising solution to ensure efficient and traceable EV battery EOL information sharing among stakeholders and compliance.

MOBI's Guideline on Implementation Guidelines for a Decentralized Cross-Border Compliant Solution will be foundational in enabling battery lifecycle data sharing in compliance with regulations and help stakeholders to achieve their circularity goals.

Courtesy of Inside Climate News

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