RECYCLING BATTERIES

Old is Gold

In this article, **Sushovan Bej** and **Toni Zhimomi** say that with the envisaged increase in electric vehicle adoption in the coming years, the increase in battery demand is imminent. This increase in battery demand would lead to faster exhaustion of minerals required to produce batteries. Hence, battery recycling undoubtedly holds an important role in the efficient use and re-extraction of the resources ensuring a stable supply chain and thereby contributing to the circular economy.

Electric vehicles (EVs) have seen a rapid growth with the global electric car stock hitting the 10 million mark in 2020 (IEA, 2021). Delhi, the capital state of India, experienced around 9% of the total vehicle sales in the last quarter of 2021 of that of EVs. This increasing shift to EVs would also mean an increase in battery demand. Lithium-ion batteries (LIBs), which currently power the EVs reached global manufacturing capacity of roughly 300 GWh per year and the production was around 160 GWh in 2020. Battery demand is set to increase significantly over the coming decade, reaching 1.6 TWh in the Stated Policies Scenario and 3.2 TWh in the Sustainable Development Scenario (IEA, 2021).

The envisaged projections in EVs and the subsequent battery demand raises important questions with regards to catering to the demand for the materials that will arise for manufacturing batteries, end-of-life (EoL), and waste management.

Battery Recycling and Technologies

The increasing demand for battery materials necessitates the need for increased extraction of raw materials. However, reserves are limited in nature and the emissions that result from extraction, processing and transport would defeat its decarbonization goals. This, therefore, necessitates the need to have a robust and efficient recycling infrastructure. It is important to note that recycling is crucial not only for securing the supply of key raw materials for the future but also for reducing the need for new mineral extraction, thereby, lowering the environmental footprint manifold.

The life of an EV battery generally ranges between 6 and 8 years and needs replacement when its capacity starts falling below 80%. There are three options post utilization of batteries for EV/traction purposes:

1. Re-use/repurpose the battery for secondary applications, e.g., stationary batteries for grid storage systems or standby use.
2. Recycle - Recover the materials in the battery such as cobalt, nickel, iron, copper, etc.
3. Landfill disposal

The sheer volume of used battery packs piled up in landfills is not an environmentally-conscious solution. Repurposing the battery is preferable to recycling as per the waste management hierarchy (Directive, E.C., 2008). Studies show that second life battery lifespan depends on its use, going from about 30 years in fast electric vehicle charge support applications to around 6 years in area regulation grid services (Lluc Canals Casals, 2019). Second life batteries start at 80% SOH and its common EoL is 60% SOH. Once the second life battery reaches its end of life (EoL), the appropriate option would be to recycle the battery. Recycling process reintroduces the recovered materials back into use, which reduces the consumption and mining of primary raw materials. This contributes to the economic cycle and forms a fundamental aspect to the circular economy. It also helps to avoid disposal of batteries in landfill. Recycling, thus, contributes to sustainability and circular economy (Kezi Cheng, 2021) and represents a viable option in managing the EV battery at its end stage. Figure 1 illustrates waste management hierarchy.

The battery chemistry with the maximum shares for EV application currently are lithium-ion battery (LIB), nickel metal hydride battery and lead acid battery, with LIBs forming the maximum share. The materials that can be recovered depends on the battery chemistry. However, currently there is a stark gap between the rate of production and rate of recycling. The gap between recycling and production currently represents an untapped source of valuable materials. Figure 2 presents battery recycling overview.

Methods of Recycling

The battery pack in an EV is usually made up of modules and each module has several cells. Each cell has an external casing, usually made from metal or plastic, which has two terminals affixed to it—a positive and a negative terminal. The positive terminal is connected to the 'cathode' and the negative terminal is connected to the 'anode'. The electrons flow in an electrolyte medium. The type of materials that make up the cathode and anode for batteries vary depending on the different chemistry types. Figure 3 shows the cutaway view of a cell.

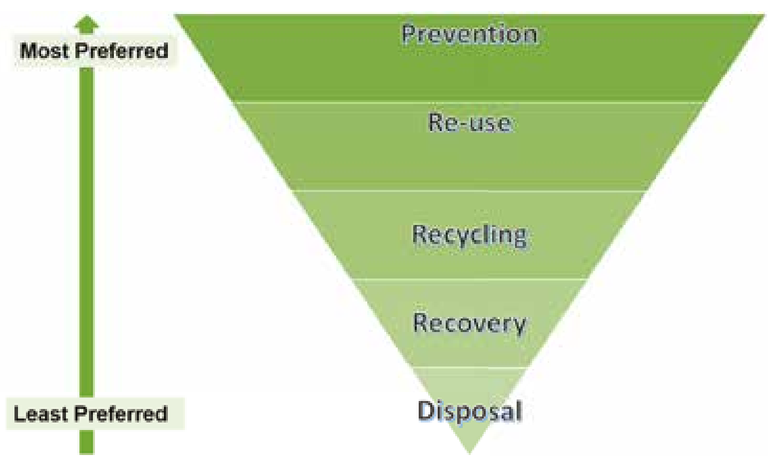

Figure 1: Waste management hierarchy

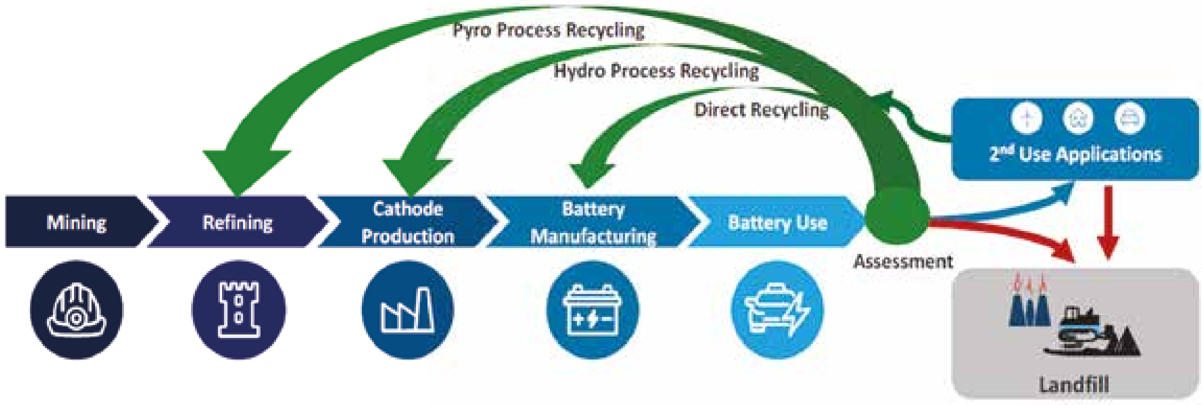

Figure 2: Battery recycling overview[1]

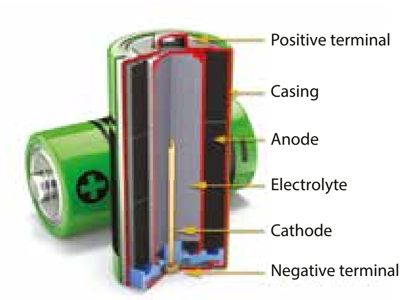

Figure 3: Cutaway view of a cell

Primarily, there are three recycling methodologies as described below:

1. **Pyrometallurgical recycling** involves the use of heat to recover metallic battery components.
2. **Hydrometallurgical recycling** consists of a series of chemical steps with aqueous solutions for the recovery of metals from the battery powder.
3. **Mechanical or physical recycling** relies on the mechanical and physical separation of battery components.

Pyrometallurgy Recycling

Pyrometallurgical recycling (smelting) uses high-temperature furnaces to burn large quantities of battery packs and combustible battery materials (e.g., graphite anode, aluminium wires, paper, and plastic casing). The process reduces the chemical components (e.g., copper, cobalt, nickel, iron) into molten metals, which are collected as alloys to be sent to metal refineries for further processing and recycling.

It recovers valuable transition metals but leaves behind a furnace slag, consisting of ashes of the burnt components and primarily containing lithium, aluminium, silicon, calcium, and some iron compounds. The key advantage of pyrometallurgical recycling is that all battery chemistries can be recycled simultaneously.

Hydrometallurgy

Hydrometallurgical recycling (leaching) uses acids to dissolve the metal components of batteries, primarily found in the cathode of LIBs, rather than using high temperatures as done in pyrometallurgy. To facilitate dissolution, battery packs are dismantled, and cells are usually further fragmented by crushing and shredding. Once the metals are brought into solution, depending on the recycling facility, several solvent extractions, chemical precipitation, and electrolysis steps may be required to separate the constituent elements as inorganic salts. This process is especially attractive for LFP and LMO cathodes, being the only method devised so far to recover any significant value from them. It can also recover electrolyte and anode materials.

This route requires certain mechanical and/or thermal pre-treatment to separate the cathode and organic materials in the batteries, which can be put through chemical processes such as leaching, precipitation, solvent extraction, etc. The hydrometallurgical route has significant lower carbon emissions and energy usage in comparison to pyrometallurgy (see Figures 4 and 5).

Direct Recycling

Physical or mechanical recycling consists of manual or automated dismantling and crushing of the battery packs to recover key components in their original state (e.g., electrodes, wiring, casing). Some recovered components (e.g., electrodes) could be used directly in the manufacturing of new batteries, whilst other components (e.g., wiring) need recycling using usual pyro or hydro schemes (as metals). In principle, the mixed metal oxide cathode materials can be reincorporated into a new cathode electrode with minimal changes to the crystal morphology of the active material. These materials can be then reused as fresh cathode material in new battery manufacturing. Figure 6 shows direct recycling of LIB.

Table 1 captures the various technologies being used to recycle EV traction batteries across the world and gives a brief overview of the processes.

[1] Argonne National Laboratory

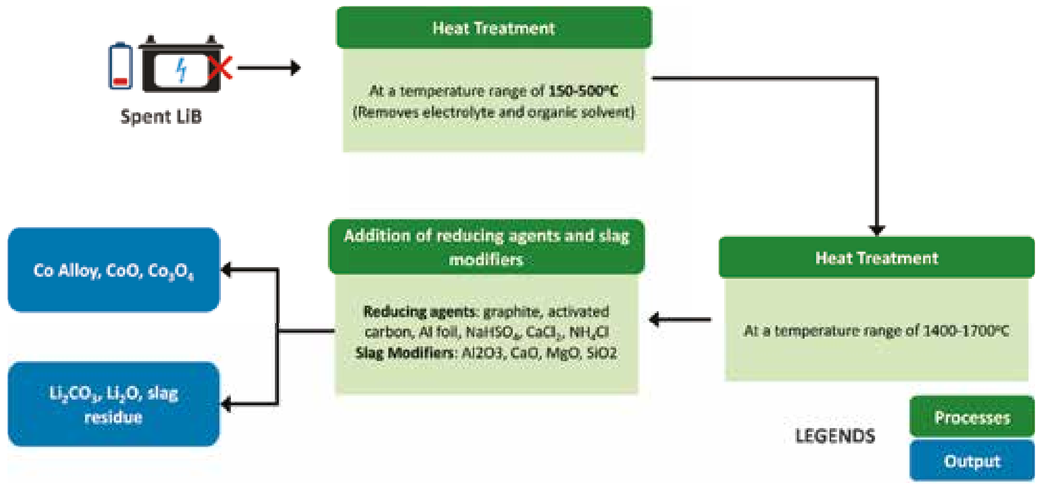

Figure 4: Generic process flow of pyrometallurgical recycling of LIB (Mohammad Assefi, 2020)

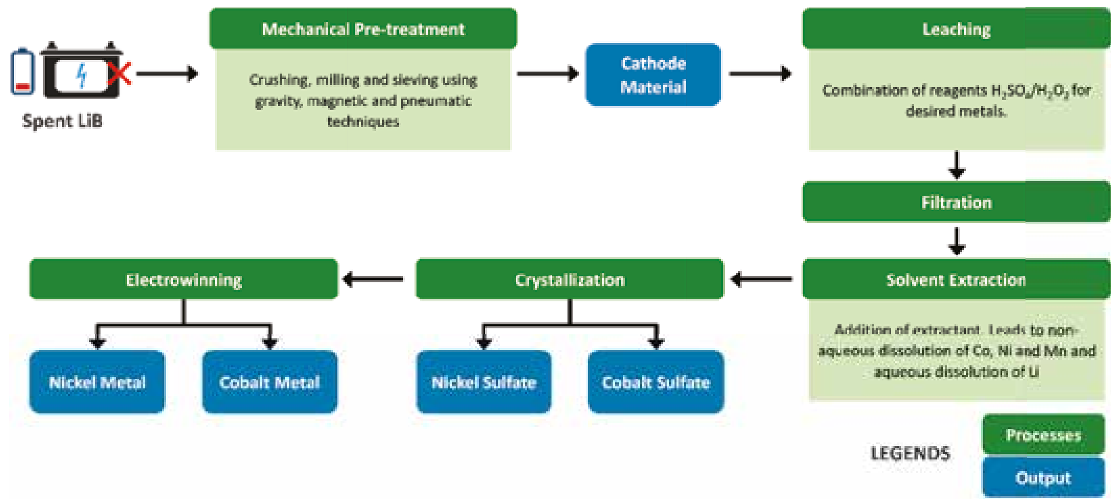

Figure 5: Generic process flow of hydrometallurgical recycling of LIB[2]

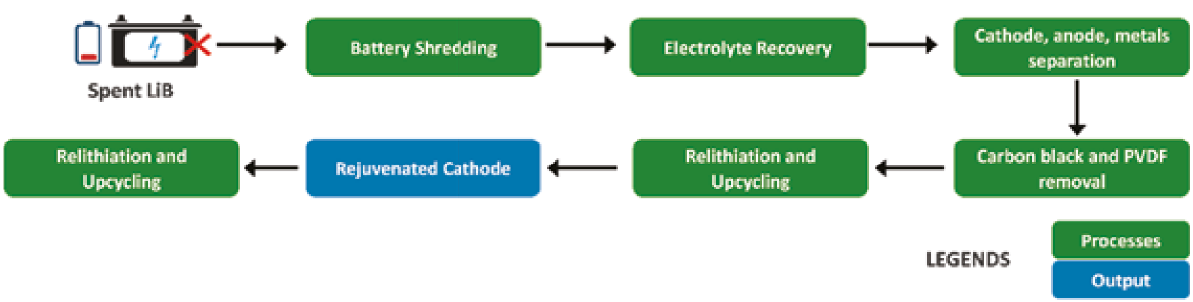

Figure 6: Direct recycling of LIB (Linda Gaines, 2021)

[2] UBS Analyst Report and GIZ compilation

Table 1: Battery recycling technologies and their uses for various chemistries

Recycling Technology / Battery Chemistry	Pyrometallurgy	Hydrometallurgy	Direct Recycling
Lithium Ion	Matured technology for recovering metal alloys » Further refinement is required to get the desired metal » Requires high capital investment, energy usage, and results in more emissions » Does not recover lithium, aluminium or inorganics » 95%–99% of cobalt, nickel, and copper can be recovered	Has a high raw material recovery rates and yield » Product purity suitable for cathode manufacturing » Can accommodate multiple batteries and cathodes » Matured technology with low basic investments and emissions » Requires prior dismantling/ discharging/ crushing » Recovery rate is generally between 85% and 90%	Avoids lengthy and expensive purification steps reducing costs. » Advantageous for low value cathodes such as LMO, LFP – technology/cathode agnostic » Most energy efficient compared to other recycling processes » Can recover anode as well » Complex process with the risk of obsolescence of technology when returned to market » Almost 100% of cathode and anode material recovered
Nickel Metal Hydride	The process doesn't require prior discharging, conditioning » Pure metal alloys are generated » Matured technology » The process is capital intensive » Energy intensive with higher emissions » Some companies have efficiency ~100% for iron, nickel and cobalt	Lower capital investment with options for recovery optimization » Recovers rare earth elements with cathode metals (>95%) and metals with efficiency >90% with electrowinning » Efficiency is highly driven by environmental conditions	Not employed for Nickel Metal Hydride batteries
Lead Acid Battery	Mainstay of both organized and unorganized lead acid battery recycling » The lead alloy generated is of high purity and the process is highly matured with nearly 100% recycling efficiency	Not generally used for lead acid batteries as pyrometallurgy provides nearly all the lead content of batteries in cost-effective manner	Not used for lead acid batteries

Figure 7 shows a simplified workflow of all battery recycling technologies on LIBs.

Challenges of Battery Recycling

» **Carbon footprint**: One of the biggest supporting arguments for promoting battery recycling is that it helps in reducing an EV's carbon footprint. However, the recycling process itself involves a number of carbon-emitting activities, starting with the emissions resulting from collecting and transporting batteries to the recycling process, which itself requires a considerable amount of electricity and thermal energy. Therefore, recycling batteries is only effective from a carbon footprint reduction perspective when the entire closed loop of battery recycling has a lower carbon footprint.

» **Economic feasibility**: Battery recycling is a complex process and requires substantial capital investment. The recycled materials may also be more expensive than newly extracted materials. This poses a threat to its overall acceptability and hence will likely require government

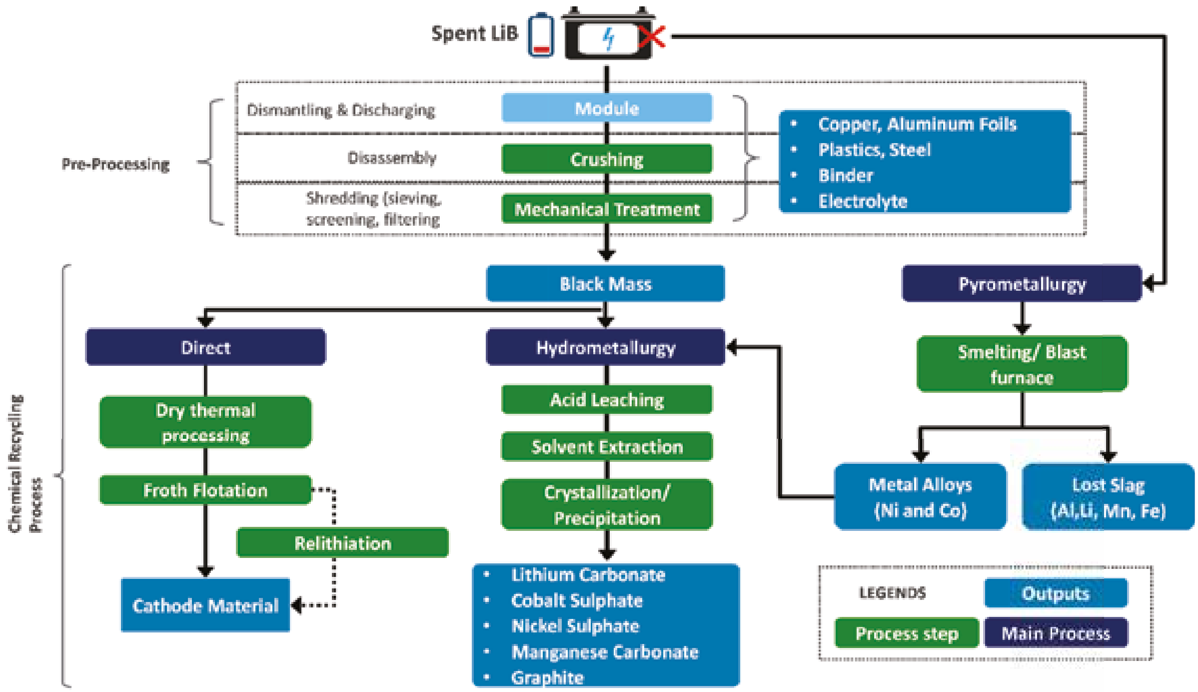

Figure 7: Simplified workflow of LIB recycling processes[3]

incentives (policies, guidelines, etc.) to promote the circular economy.

» **Evolving design and technology**: Batteries are subject to constant R&D to enhance their chemical composition. As a result, there is a question on the feasibility of using the materials recovered from 10–12-year-old batteries to meet the needs of new generation batteries.

» **Traceability of recycled materials**: LIBs can be used in less demanding applications once they are taken off from their first-life applications. The secondary usage may appear to be more feasible than recycling (due to the high cost of the latter) and thus batteries may ultimately end up in a landfill after their capacities gradually wear off. Thus, a monitoring or reporting system should be in place to enable traceability of recycled battery materials, which is challenging to implement.

» **Quality of recycling**: Materials from improper or substandard recycling could lead to battery explosion causing threat to life and property. Therefore, battery recyclers need to adhere to the highest quality standards to ensure the purity of the material recycled.

Global Practices on Battery Recycling

Germany

The European Battery Directive 2006/66/EC adopted in Europe from September 26, 2006 requires European countries to transpose the Directive into national law. The aim of the Battery Directive is to increase the percentage of batteries that are returned and recycled, because they contain not only valuable raw materials but also substances that are environmental and health hazards. It sets limits for the use of harmful substances such as lead, mercury, and cadmium. The Battery Directive requires manufacturers, distributors or importers of batteries to contribute to the cost of disposing of the batteries.

With reference to directives 2006/66/EC of European Union, Germany has her policy named Batteries Act 2015 in the same line. The Batteries Act differentiates between portable, industrial, and automotive batteries for the purpose of collection. The Batteries Act restricts the percentage of mercury and cadmium in batteries to not more than 0.0005% and 0.002% (by wt). The main amendments are:

» A notification of registration obligation to all manufacturers of batteries

» Establishment of minimum standards for containers used by the collection schemes for collection and pick up

» New responsibilities and framework for the approval of manufacturers' collection schemes

» Incorporation of the waste electrical and electronic equipment (WEEE) register foundation into manufacturer registration and the approval of collection schemes as well as enforcement in this area.

[3] Based on discussions by GIZ India team with the industry stakeholders.

China

In 2018, the Ministry of Industry and Information technology (MIIT) issued "Interim Measures for the Administration of Recycling Traction Batteries of New Energy Vehicles", also called the "Interim Measures", to promote comprehensive utilization of resources, protect the environment and human health, ensure safety, and promote the sustainable and healthy development of the new energy automotive industry. The Interim Measures stipulate the design, production, and recovery responsibilities of traction batteries, the comprehensive utilization of traction batteries, and their supervision and administration. The key details from the interim measures are:

» Manufacturers of EVs are responsible for setting up facilities to collect and recycle spent batteries.
» The carmakers must also establish a maintenance service network allowing members of the public to repair or exchange their old batteries conveniently.
» Together with battery makers and their sales units, carmakers must also set up a "traceability" system enabling the identification of owners of discarded batteries.
» Battery makers are also encouraged to adopt standardized and easily dismantled product designs, to help automate the recycling process. They must also provide technical training for car makers to store and dismantle old batteries.
» The guidelines encourage battery-makers to strengthen cooperation with companies that can make a better and rational use of used batteries removed from new energy cars. Today, Guidelines are not subject to penalties or incentives.

A timeline of the various waste battery-related regulations that were notified in China[4] is shown here.

United States (US)

In May 1995, the US Environmental Protection Agency (EPA) promulgated the Universal Waste Rules to reduce the amount of hazardous wastes entering the municipal solid waste stream, encourage the recycling and proper disposal of certain common hazardous wastes, and reduce the regulatory burden on businesses that generate these wastes by simplifying the applicable regulations and making them easier to comply with. The Universal Waste Rule, however, does not automatically apply in each state.

On May 13, 1996, the Mercury-Containing and Rechargeable Battery Management Act (the Battery Act) was signed into law. The Battery Act applies to Battery and Product Manufacturers, Battery Waste Handlers, and certain Battery and Product Importers and Retailers, not consumers. Specifically, the Act:

» Establishes national, uniform labelling requirements for Ni-Cd and certain SSLA rechargeable batteries.
» Mandates that Ni-Cd and certain SSLA rechargeable batteries be "easily removable" from consumer products. A battery can be easily removed if it is detachable or removable from the product with the use of common household tools.
» Makes the Universal Waste Rule effective immediately in all 50 states for the collection, storage, and transportation of batteries covered by the Battery Act.
» Requires EPA to establish a public education programme on battery recycling and the proper handling and disposal of used batteries. EPA is required to consult with manufacturers and retailers to carry out this initiative.
» Prohibits, or otherwise conditions, the sale of certain types of mercury-containing batteries (i.e., alkaline-manganese, zinc-carbon, button cell mercuric-oxide, and other mercuric oxide batteries) in the United States.

Indian Scenario

On May 15, 2001, the Ministry of Environment and Forest (MoEF),

Legislations related to waste batteries in China.

Laws and regulations	Year	Major regulations on battery recycling
Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution	1995	Waste batteries are dangerous solid wastes and need to be recycled separately
Technical Policy for the Prevention and Control of Hazardous Waste Pollution	2001	Phase-out batteries containing mercury and cadmium
Policy on Pollution Prevention Techniques from Waste Batteries	2003	Battery industries should take responsibility for collecting waste batteries and for proper labeling
National Hazardous Waste List	2008	Lead-acid batteries are dangerous solid wastes that need to be collected and treated separately
Administrative Measures on the Collection and Using of Waste Electrical and Electronic Product Treat Fund	2012	Manufacturers or importers are responsible for the fund collection
Directory of Waste Electrical and Electronic Equipment Treatment (2014)	2015	Waste LIBs were officially added to the scope of the Fund
Technology Policy for the Recycling of Power Battery (2015 edition)	2016	Provisions on the recycling and utilization of waste EV batteries
Policy on Pollution Prevention Techniques of Waste Batteries	2016	The pollution prevention and control technologies of waste LIBs
The Implementation Plan of the Extended Producer Responsibility System	2016	Implement the extended producer responsibility system for batteries
The Interim Measures for The Management of Power Battery Recovery and Utilization of New Energy Vehicles	2018	Automobile manufacturers should shoulder the primary responsibility for power battery recovery
The Interim Provisions on The Traceability Management of Power Battery Recovery and Utilization of New Energy Vehicles	2018	The comprehensive management platform for national monitoring and power battery recovery and utilization traceability of new energy vehicles must be established
The Notice on the Pilot Work of Power Battery Recycling of New Energy Vehicles	2018	Confirmed some pilot regions and pilot enterprises to carry out the pilot work of power battery recycling
The Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution (2020 edition)	2020	The establishment of a credit record system for the prevention and control of solid waste (including waste LIBs) pollution
The Notice on Matters Related to the Total Ban on Solid Waste Import	2020	The import of solid waste in any way is prohibited

[4] GIZ compilation

Government of India, notified the Batteries (Management and Handling) Rules, 2001 to regulate the collection and recycling of all the used lead-acid batteries in India (Ministry of Environment and Forest (MoEF), 2001). The rules as mentioned limited the definition of a battery to a 'lead acid battery' and Li-ion batteries were not covered under. The Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, published the Draft Battery Waste Management Rules, 2020 on February 20, 2020, which is to supersede Batteries (Management and Handling) Rules, 2001 (Ministry of Environment, Forest and Climate Change (MoEFCC), 2020). The Draft Rules brings under its ambit, all manufacturers, producers, collection centres, importers, re-conditioners, re-furbishers, dismantlers, assemblers, dealers, recyclers, auctioneers, vehicle service centres, consumer and bulk consumers involved in manufacture, processing, sale, purchase, collection, storage, re-processing and use of batteries or components thereof including their components, consumables and spare parts, which make the product operational.

As per our discussions with the industry recycling of lead-acid batteries is mostly informal (75%–80%) in nature, that is, by means of recycling through *kabadiwalas* and unregistered recyclers. The LIB recycling generally follows a mix of formal and informal recycling, given the fire safety aspects related to such type of batteries.

The following points should be considered while preparing the rules/ guidelines for battery recycling in India:

- Need for a separate operational guideline for EV/automotive batteries, given their size (compared to other e-waste) and the envisaged scale.
- Identify the feasibility of battery recycling and the fund support required for sustenance of such businesses in India.
- Need to develop rules/operational guideline, where all the roles and responsibilities are to be undertaken by private sector, while a public institution is undertaking monitoring of the value chain.
- Need for compulsory implementation of battery recycling guidelines with stringent monitoring and appropriate penalization for non-adherence.
- Need to mandate submission of Extended Producer's Responsibility (EPR) plan by all the stakeholders in the EV value-chain such as, EV Manufacturers, EV Manufacturer's Dealerships, Battery manufacturers, Battery vendors & dealerships, Charging Infrastructure and Battery Swapping Operators for collection of batteries from consumers.
- Need to mandate tagging of batteries for data generation and tracking batteries along the value chain.
- The list of collection centres for submission of batteries by the consumers should be made publicly available by all the stakeholders in the EV value-chain.

The above considerations would enable development of a holistic EV battery recycling ecosystem for India.

Conclusion

With the envisaged increase in EV adoption in the coming years, the increase in battery demand is imminent. This increase in battery demand would lead to faster exhaustion of minerals required to produce batteries. Hence, battery recycling undoubtedly holds an important role in the efficient use and re-extraction of the resources ensuring a stable supply chain and thereby contributing to the circular economy. However, the scale at which battery recycling can contribute significantly has not been achieved yet owing to many reasons. Efficient battery waste management policies and regulations are the need of the hour to encourage participation from the industry and the entire ecosystem, appropriate technological assistance to sort and recover materials. Although safe handling of batteries especially LIB, environmental impacts due to battery recycling and issues regarding standardization of batteries can enable automation of the recycling process in the future, a viable and thriving battery recycling industry can easily address this challenge.

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