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A Systematic Review of Optimizing Electric Vehicle Battery Recycling Network

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Abstract: ***Recycling of batteries is one of the important ways to recover the materials of a retired battery. This review analyses current recycling technologies and methods, explaining their cost and environmental impacts associated with EV batteries. It explores the challenges faced in recycling. Also, it includes technological inefficiencies, economic considerations, fluctuations in raw material prices, and greenhouse gas emissions associated with recycling. Factors like the volume of end-of-life batteries, the impact on the environment, and transportation costs are examined. The review provides actionable insights for enhancing recycling processes. The outcome aims to help electric vehicle manufacturers and researchers to develop more efficient, cost- effective recycling systems.***

Keywords: Electric Vehicle, Pyrometallurgical Process, Hydrometallurgical Process, Recycling batteries.

1. Introduction

Batteries are a vital part of Electric Vehicles (EVs), and were employed in tandem with their broad acceptance in the upcoming years. Lead-acid, Nickel-Metal Hydride, Lithium-ion, and Nickel-Nickel Chloride are the four main Electric Vehicle Battery (EVB) variants that are now in use. The most popular EVBs in the market are Lithium-ion Batteries (LIBs) which are unquestionably superior to other EVBs in terms of cost, increased cycle life, Nickel metal content, and high specific capacity.

It is anticipated that the worldwide compound annual growth rate of LIBs will increase by 36% due to the expansion of EV industries [1]. Each material or component used in manufacturing of EV battery is affecting badly on environment and on the public health too. Additionally, if these components are disposed of in landfills from the Retired Batteries (RBs), they run the risk of leaking and contaminating nearby water sources. As a result, the proper disposing of so many EVBs is a pressing issue today.

According to a study released by the Centre for Transportation at Argonne National Laboratory, [2] material charges 80%, Labor charges 10%, and overhead charges are about 10 %of an EV battery's total production costs respectively.

Remanufacturing old batteries is one possible strategy to reduce battery prices since material cost reductions from recycled EVBs are crucial. The rapid depletion of lithium due to its rising use in EVBs emphasizes

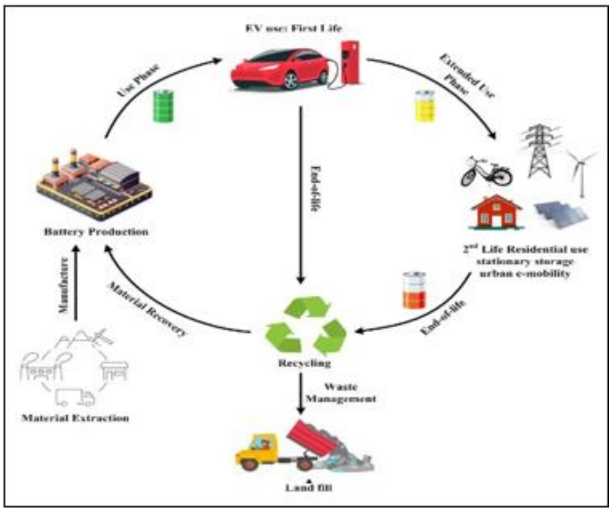

Figure 1: Structure of Battery recycling

the necessity of reducing raw material use through recycling. Issues related with the recycling of EVB's like Battery traceability management, cost management reduction in environmental contamination, reduction in manufacturing cost and raw material conservation are the main issues that need to be studied to increase the efficiency of EVs. Such a strategy is very advantageous [3]. The structure of battery recycling in a circular economy perspective is shown in Fig.1.

Many references given in this review give clear ideas about different types of batteries, their cell chemistry, and their detailed analysis along with the advantages and disadvantages of different recycling methods. Battery, their components, and effective charging and discharging methods are explained in many reference papers. The challenges of EV battery recycling, their cost effectiveness, metals receiving after recycling and their prices are explained with detailed analysis and also explained in many references.

This review explores the details of different recycling systems

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recently in use. A comparison of different recycling systems is tabulated to give an idea about the effective methods that can be used for recycling of battery. The battery demand, cost, and Environmental Impact of Recycling along with challenges in recycling are also explored.

The essence of this review article is spread over as follows: It starts with an introduction in Section I, Battery Recycling Network is in Section II, Section III consists of Recycling processes and analysis, Challenges of Recycling in Section IV, Section V deals with LIB recycling as it is attractive Energy Storage for EV and the general discussion and existing gaps in terms of conclusion are in briefed in Section VI and Section VII respectively.

1) Battery Recycling Network

The recycling network consists of four nodes. Recycling center, EVB processing center, Remanufacturing center, and center for disposal of waste [4]. End-of-life (EOL) batteries are collected at the recycling center which are collected from the customers and sent to the EVB processing center. The initial testing of the battery is done at the EVB processing center. According to the remaining capacity of the battery, batteries are divided into three categories: T_1 (Remaining capacity more than 80%), T_2 (Remaining capacity more than 60% and less than 80%), and T_3 (Remaining capacity less than 60%) [5]. Based on the category, the battery recycling process is shown in the process flow in Fig. 2.

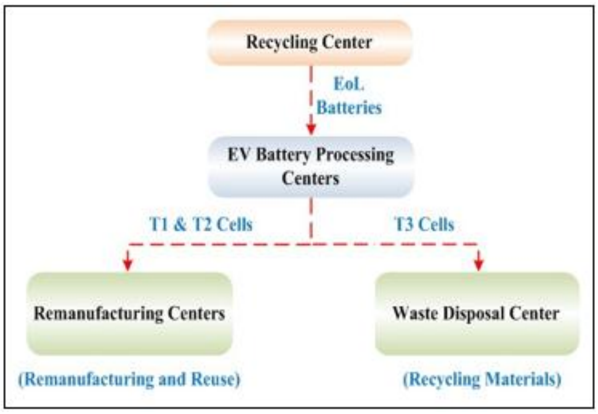

Figure 2: EV Recycling Process after EOL verification

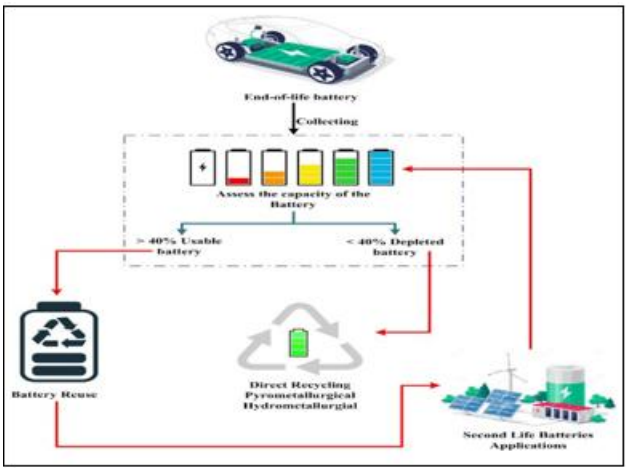

Figure 3: Electric vehicle battery recycling process

2) Battery Recycling Process

The factors pushing LIB recycling include metal pricing, preservation of raw materials, toxicity reduction in the environment, CO_2 emissions reduction, reduce energy consumption, and trash reduction [5]. Apart from Lithium, metals including aluminium, cobalt, iron, manganese, and nickel may also be extracted using LIB recycling.

The range of components, which includes various physical configurations, cell kinds, and characteristics, presents the difficulties in recycling of LIBs. In most of the cases, the initial stage of the LIB recycling procedure is pretreatment. After the battery discharges, the electrodes, pack, and BMS (Battery Management System) all shut off. The main categories of recycling procedures are discussed in the following sections.

a) *Pyrometallurgy*

The pyrometallurgical process requires high temperatures, typically above 1400 degrees Celsius to melt the batteries and convert the metal oxides into an alloy of Cobalt(Co), Copper(cu), Fe, and Ni which are mainly leachable [6]. The main problems with this type of process are they use a lot of energy, lose a lot of material, and emit dangerous gasses. Some benefits include lower costs and time, faster processing, higher quantities more effectively achieved, and more flexibility resulting from the possibility of combining various packs of utilized LIBs. Moreover, black matter, which contains valuable metals, cannot be used to extract lithium [7]

b) *Hydrometallurgy*

Metals are eliminated from the cathode using aqueous (like water) solutions. The active components are separated using water and other acids, which often yield compounds of nickel, lithium, and cobalt. This method has the advantage of using less energy, recovering high- purity metals, more efficiently, and recovering lithium as lithium carbonate. Furthermore, this process produces minimal gas emissions. Chemical precipitation, solvent extraction, electrochemical deposition, and leaching are the most often used hydrometallurgical procedures for extracting black matter elements. Because, leaching is hampered by contaminants like highly selective agents, pretreatment steps must be finished before starting this process [8]

c) *Direct Recycling*

This is one of the direct methods of recycling. This method will directly recover the active metals of LIB's. It will retain the original compound structure of the battery [9]. In this process, the battery constituents are separated by physical separation methods. Magnetic separation and moderate thermal processing methods is used to avoid chemical breakdown of the active materials. By removing the battery's exterior shell and isolating precious parts, the physical processing stage seeks to reduce scrap.

Physical separation techniques include magnetic stirring, filtration, screening, and crushing to recover materials. Flotation is sometimes used to separate polymers and casings.

There are four types of physical separation: density, size, magnetic, and flotation separation [10] The procedure of separating one component from the others is called mechanical treatment. Processing by hand is not as efficient as mechanical treatment when dealing with the amount of

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material involved in the recovery process.

To recover the Steel, Copper, and Aluminium foil that make up around 25% of the total value, the batteries are crushed partially and the components gets physically separated. When it comes to Lithium recovery, hydrometallurgy has a major advantage over pyrometallurgy. Li_2CO_3 precipitation is used to recover Lithium after the purification of the leaching solution. A comparison of the main recycling methods is displayed in Table I.

2. Challenges of Recycling

The following parameters were observed as a challenge for battery recycling:

1) *Fluctuation in Raw Material Price*

Raw material procurement is dependent on the rate of imports. Changes in raw material costs have a substantial effect on the business model, and any decline in pricing harms the recycling sector [11].

2) *Battery Chemistry*

Lead acid batteries have a simpler chemistry than LIBs and are commercially recycled all over the world, In the hydrometallurgy method of recycling the solubility property of lithium and transition metals in acid is used [12]. The chemistry of Lithium is continually developing to increase energy density, effectiveness, and safety, which presents several challenges for recyclers in accurate batteries are limited [14]. Hence, Battery chemistry is one identifying and recovering material from different batteries [13]. As far as India is concerned, it is heavy reliance on battery imports as the production of Lithium of the important parameters that need to be studied in detail while considering recycling.

3) *Material Collection*

The National Institute of Transforming India (NITI) aimed to have 30% of EVs in India by the end of the year 2030 [15]. Hence, the government must think about the trash collection from EVBs and the recycling process. Currently, most of the industries and individuals in India are not aware of the recycling and material collection process. Hence, the ignorance and advantages of recycling and metal collection leads to significant bottlenecks of recycling in India. All government sectors must develop strict policies and regulations for the same

4) *Value of Recovered Metal*

The recovery of important raw materials and the benefit- to-cost ratio of batteries are directly impacted on recycling efficiency. Other than lead, several metals included in batteries have recycling efficiencies between 50% and 68%. These metals may be recycled without losing their inherent qualities. Because of their straightforward chemistry and structure, lead batteries can be recycled 90% of the time. These metal's economic value is based on how well they can be

Table I: Comparison of Main Recycling Process

	Merits	Demerits
Pyrometallurgy	Adaptable and suitable for any battery	Not suitable for Li and Al extraction
	Pretreatment is not necessary	Expensive gas clean-up is necessary to prevent air pollution.
	Excellent recovery of Co, Ni, and Cu	Energy-intensive and Capital-intensive
	Dependable technique that may be applied with current pyrometallurgical facilities	Further refining is needed to convert metal alloys produced during the smelting process into elemental metals.
Hydrometallurgy	Suitable with any battery type and arrangement	Battery cells must be crushed, which raises safety issues.
	ability to modify recover and separation processes to focus on certain metals	The acid dissolves the cathode structure.
	High product purity and high recovery rates (for example, lithium) (ideal for cathode precursors, etc.)	A significant volume of effluent from processes that has to be disposed of or recycled
	Energy-efficient and No air emissions	Not economical for Lithium iron phosphate batteries
Direct	Retains valuable cathode structure	Separations and intricate mechanical pretreatment are necessary.
	It is possible to recover almost all battery components, including the anode, electrolyte, and foils.	When recovered material is released onto the market, it could not function as effectively as virgin material or it might become outdated.
	appropriate for LFP batteries	Combining different cathode materials might make recycled products less valuable.
	Energy efficient	Regeneration processes yet to be developed
	Easy to recycle manufacturing leftovers	Not developed to an industrial scale

recycled 90% of the time. These metal's economic value is based on how well they can be recovered. The London Metal Exchange provides precious metals, such as Nickel and Cobalt, which have limited worldwide quantities [16]. The percentage of Metal recovery in the recycling process is tabulated in Table II.

Table 1: Recovery metals and efficiency

Metal	Value of metal US $ / Tonne	Recycling efficiency (%)
Nickel	13796.00	69
Primary Aluminium	1771.07	61
Lead	1899.68	91
Cobalt	33557.25	58
Lithium Carbonate	9251.00	56
Lithium Hydroxide	11251.00	56
Manganese (44%)	7.70	58

The retired Lithium-ion batteries have a much higher percentage of high-value elements, like Cobalt, Lithium, and Nickel. They are present in higher concentrations than in natural ores [17]. The NMC111 (LiNi0.33, Mn0.33, Co 0.33O2) batteries are the most profitable type of Retired Batteries to recycle. From recycling of NCM111 battery, the recycler could earn around 42 USD per kilowatt hour [18], whereas, Lithium Iron Phosphate (LFP) batteries had the lowest salvage value of around USD 15 USD per kilowatt hour.

The analysis of Recycled EV Batteries by battery type and Cathode Chemistry in the year 2020 is depicted in Fig.4. The cost of recycling EV batteries varies concerning chemical composition. LFP batteries are the cheapest to recycle, while NMC and NCA batteries are more expensive due to their higher content of valuable metals. In materials recycling, the minerals required in LIBs depend on the chemistry of the cathodes, but the key materials are Lithium, Cobalt, Nickel, Graphite, and Manganese [19].

5) *Greenhouse Gas Emission Due to Recycling*

Recycling has been demonstrated to assist in reducing greenhouse gas emissions from the environment by conserving energy during the first phases of mining, transportation, and battery production [20]. Most prior research indicates that recycling contributes to the reduction of overall greenhouse gases. However, a more comprehensive knowledge of greenhouse gas reduction may be obtained by examining the process of recycling. The quantified amount of CO_2 emissions at different phases was observed when the life cycle assessment of LIB was done using a hydrometallurgical process by the Swedish Environment Research Institute [21].

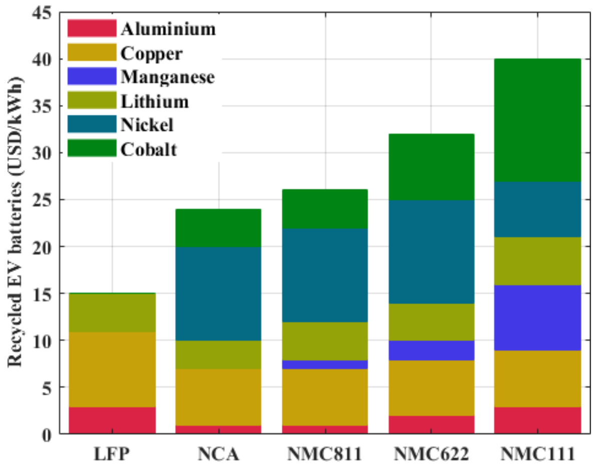

Figure 4: Analysis of Recycled EV Batteries by Battery Type and Cathode Chemistry in 2020

reduction may be obtained by examining the process of recycling. The Swedish Environment and Research Institute evaluated the life cycle assessment of LIB and recycling by hydrometallurgical process, which included quantified CO_2 emissions at various phases [21].

3. Discussion

As more people utilize portable gadgets, the need of batteries in Renewable Energy Sources (RES), and EVs, are growing exponentially. This demand is propelling advances in battery technology and recycling methods to address environmental and resource issues.

A. *Battery Demand*

Storage battery is essential part of day to day life of human being. In every application we need energy in the form of storage. Hence battery demand is increasing as energy demand rises. Primary batteries are throwaway batteries that are frequently found in remote controls for air conditioners, televisions, and toys. Rechargeable secondary batteries have been utilized in commercial applications for a considerable amount of time. Over the years, several secondary battery technologies have emerged. Nevertheless, LIB storage continues to be the most widely used, making up over 88% of newly installed capacity in 2016. According to Allied Research, The market for recycling batteries from electric cars will grow to 2272.3$ million by 2025 from $138.6 million in 2017 [22].

B. *Battery Recycling Technology*

Lead and LIB are combined in modern recycling technologies to salvage important materials from used batteries. Lead acid batteries are sufficiently developed, and recycling them requires just basic knowledge. Today, recycled lead-acid batteries make up 50% of the lead supply. Advanced LIBs can be recycled to lead acid batteries. However, because of the battery's special metal characteristics and structure, it is challenging to recover Li and other precious and significant components.

Two recycling technologies hydrometallurgy and pyrometallurgy have been extensively employed by a variety of sectors since the advent of modern batteries. In certain cases, both these methods may be combined to increase efficiency.

C. *Lead-Acid Battery Recycling*

Recycling lead-acid batteries consists of three different processes, breaking, crushing, and physically separating the batteries into lead oxide (PbO), polypropylene (C3H6), plastic, sulfuric acid (H2SO4), and lead oxide/sulphate paste. Batteries are recycled using conventional pyrometallurgical techniques as the lead acid battery industry has expanded. Fly ash, a by- product of smelting, contains Lead (Pb), Zinc (Zn), Copper (Cu), Cadmium (Cd), Mercury (Hg), and other toxic metals [23]. Unmanaged battery waste is extremely dangerous for the environment.

D. *Lithium-ion Battery Recycling*

The thermal technique of pyrometallurgy involves using heat to separate materials. Heating causes a thermal reaction, which transforms the material. The susceptibility of the metal to heat determines the degree of material recovery. Metal can burn at high temperatures, producing a lot of gas and slag. This method has an environmental cost as it uses a lot of energy and releases CO_2, furans, and dioxins into the atmosphere. To heat the electrolyte, the furnace temperature is kept below 300°C in the pre-heating zone. Although these elements are recovered as alloys, they are lost as slag, especially Aluminium (Al), Lithium (Li), Silicon (Si), Magnesium (Mg), Cobalt (Co), Copper (Cu), Iron (Fe), and Calcium (Ca) [24]. Hydroxide precipitation is used to remove

Copper and aluminium during the purifying process.

E. Lithium-ion Battery Recycling

The Ever Batt and GREET models are used to determine the impact of recycling on cost and the environment [25]. The cathode chemistry market share of retired batteries from the material flow analysis (MFA) is used to determine the cost and environmental impact of recycling 1 kg of pack-level LIB materials for each year. The avoided emissions from recovered materials were determined by taking the materials recovered and calculating the equivalent virgin material impacts using the GREET life cycle.

The variation in battery and EV cost comparison is shown in Fig. 5(a) and Fig. 5(b), respectively. It is observed that due to improved recycling techniques, the overall cost of EVs is decreased as compared to the cost of battery . Even if the cost of the battery is kept constant for analysis the overall cost of the battery is observed to be less, No subsidies are considered while making this analysis.

F. Merits and Demerits of the Recycling Process

Reusing LIBs provides several benefits in a range of domains. Refineries and mining have less of an effect on nearby towns. It is commercially feasible to recover metal from batteries [26]. Because EVBs may be poisonous and damaging to the environment if disposed

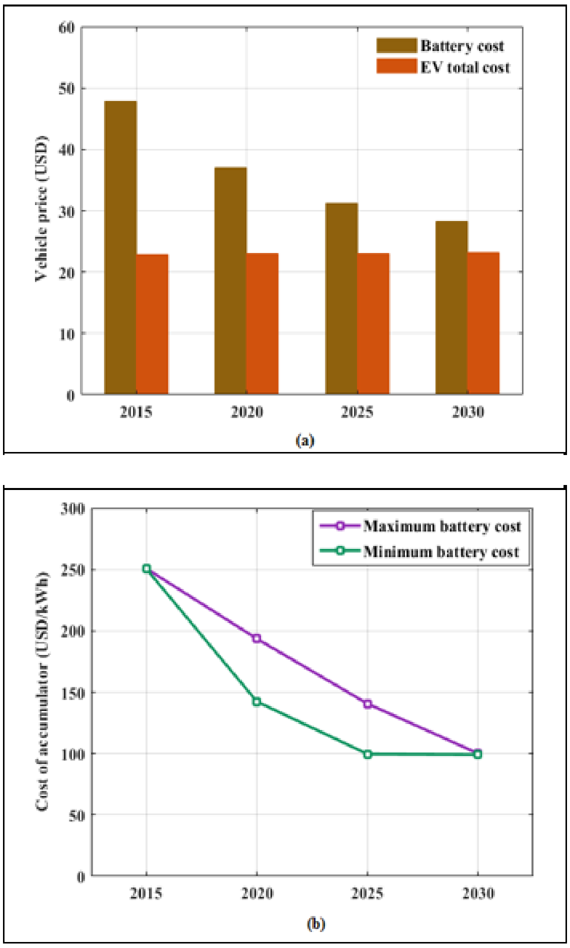

Figure 5: EV battery cost assumptions (a) Battery and EV total cost (b) maximum and minimum battery cost

of inappropriately, recycling helps in reducing Green House Gas (GHG) emissions. Benefits to the supply chain include recovering rare raw resources, lowering the demand for these goods, and reducing dependency on imported commodities [27].

Currently, there are several issues with the recycling process, like inadequate Government rules and regulations, safety, method of transportation, storage batteries, and logistical challenges. Furthermore, because heating the molten metals and oxides needed to make batteries requires a lot of energy, air pollution, solvent toxicity from process extraction, acid discharge into rivers during leaching, and other factors, the recycling process is still expensive and potentially harmful to the environment. The pros and cons of recycling are tabulated in TABLE III.

Table III: Merits and Demerits of Recycling

Process	Merits	Demerits
Collection and Transportation	Regulated handling	Logistical challenges
Recycling Methods (Hydrometallurgical & Pyrometallurgical)	Effective metal recovery /Versatile	High environmental impact and cost
Recovery of Rare Earth Elements	Effective recovery /Improved efficiency	Complex processing and Precise control are needed.
Black Mass Purification	Efficient contaminant removal and maintaining performance	Complex process and Limited scalability
Circular Economy Strategies for Battery	Encourages repair /reuse and Reduces new material reliance	Variable implementation and Requires collaboration.

G. Finding of this Review

Some critical gaps that require further exploration are-

1) The economic impact of fluctuating raw material prices on recycling sustainability must be studied thoroughly, with dynamic models to manage economic uncertainties.
2) Inadequate collection systems of EOL batteries and to create public awareness for effective recycling.
3) Comprehensive life cycle assessments of recycling processes, including all environmental impacts, and detailed research into recycling technologies for components like graphite and electrolytes are lacking.

4. Conclusion

This systematic review of optimizing EVB recycling networks highlights the critical need for effective recycling strategies as the adoption of EVs continues to grow. Owing to the pressing necessity of recycling RBs for EVs, this review developed a model that considers many battery management techniques. The volume of RBs, carbon taxes, and transportation costs are the three main parameters identified by the model as impacting the recycling network's greatest design. This analysis shows that modifications to these crucial elements can impact both the overall cost and network architecture, with processing costs having the greatest impact and carbon tax having the least impact. The review identifies several challenges in the recycling network, such as the complexity of battery chemistries, variability in battery types, and logistical issues in collection and transportation.

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