Harnessing Sustainability: The Global Journey of Recycling Electric Vehicle (EV) Batteries

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I. Abstract

This paper examines global initiatives focused on recycling electric vehicle (EV) batteries, which are crucial for modern transportation systems. As electric mobility expands, the demand for effective recycling of lithium-ion batteries (LiBs) grows, presenting both environmental opportunities and challenges. The paper reviews international policies regarding EV battery recycling and highlights collaborative efforts, such as the EU-India Clean Energy and Climate Partnership and the Global Battery Alliance. These initiatives aim to advance recycling technologies and reduce the environmental impact of battery production. However, significant obstacles persist, including the high cost of recycling, insufficient infrastructure, and regulatory gaps. To secure a more sustainable and environmentally responsible future for electric mobility, innovation and improved recycling frameworks are essential.

Keywords: *Electric vehicles, battery recycling, lithium-ion, global sustainability, environmental policies, international collaboration.*

II. Introduction

Electric vehicle batteries provide rechargeable power that drives electric motors which power both BEVs and HEVs. These batteries facilitate the development of current efficient transportation systems because they represent significant progress toward a healthier environment.

The batteries used in these systems consist of Lithium-ion Batteries (LiB) that achieve both high-density power storage and lightweight operation. Most battery technologies available today show specific energy levels below those of liquid fuel which results in larger vehicles or limited driving ranges. Evolutionary devices harness the dual strengths of a strong power-output ratio with high energy efficiency and durable temperature endurance with a long lifespan, leading to long-lasting efficient performance. The high expense of material recovery stands as a main obstacle to lithium-ion battery recycling despite the availability of recycling methods for multiple battery elements.

EVs represent a new market segment so battery recycling of this technology remains in its first developmental phase. The International Council on Clean Transportation reported during the conclusion of 2022 that annual battery material recycling capabilities reached 105,150 tons of capacity based on existing technology levels.[1] The raw materials entering recycling facilities do not originate from retired EV batteries. Scrap materials produced from EV battery production account for the majority of materials that pose significant environmental dangers worldwide.

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

1. Reuse/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

[1] ICCT

In recent years, a considerable number of national and international efforts have been initiated by the private and public sectors in LiB recycling.

III. Recycling Policies and Regulations Worldwide

A. India:

The Indian transition from conventional fossil-powered vehicles toward electric vehicles will boost LiB battery consumption in the upcoming years. Electric vehicles mostly use lithium nickel manganese cobalt (LNMC) together with lithium iron phosphate (LFP) battery technologies in their current variants. The nation plans to produce 500 gigawatts of clean power before 2030 while working to establish itself as a worldwide leader in clean power manufacturing of solar cell panels and wind turbines. By 2030 it is anticipated that the total elected amount of LiBs that have been retired from EVs together with their use in secondary applications will exceed 70 GWh. Proper recycling methods will enable the recovery of approximately 90% of these LiBs.[2]

The current situation in the nation shows a lack of technology-based solutions for LiB waste collection and storage together with recycling processes. There are no binding laws or regulations which govern the procedures for handling retired LiBs from the outset to the end stage of their disposal. For widespread renewable and stationary applications to achieve cost-effectiveness the establishment of guidelines regarding second-use solutions for used EV batteries is necessary.

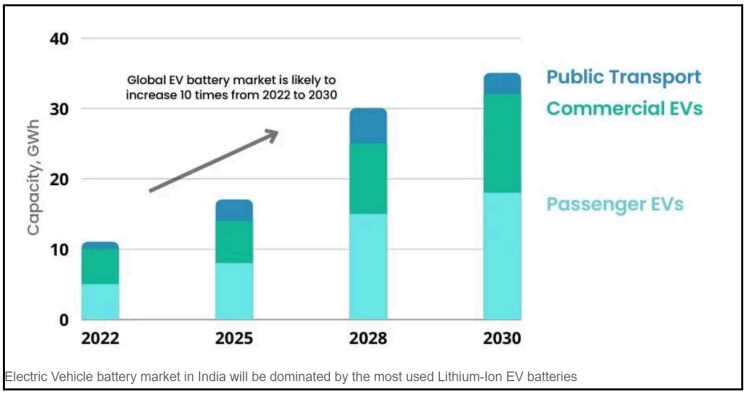

Image 1: EV Battery Recycling Market in India.[3]

1. Battery Waste Management Rules:

The Battery Waste Management Rules received approval by the Ministry of Environment, Forest and Climate Change, Government of India through their implementation on August 24, 2022. The Battery Waste Management Rules of 2022 functions as a replacement system to the Batteries (Management and Handling) Rules from 2001 to regulate Electric Vehicle batteries alongside portable automotive and industrial batteries. Waste battery management follows these rules which protect the environment during proper waste management.

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[2] Projected Retired LiB Volume and Recycling Potential in India by 2030

[3] EV Battery Recycling Market in India

These Battery Waste Management Rules of 2022 establish their foundation through Extended Producer Responsibility (EPR). The Extended Producer Responsibility (EPR) mandates that producers such as battery importers carry out waste battery collection and recycling or restoration. The regulation promotes the use of recovered waste battery materials to produce newer battery models. All recycling rules forbid the disposal of waste batteries at landfills and the burning of them through incineration.

The rules support the formation of industrial activities focused on waste battery collection and recycling alongside refurbishment services. The regulations enforce material recovery minimums to unlock new industrial technologies and recycling investments which generates fresh business prospects. The incorporation of established recycled material levels in battery production creates prospects to reduce raw material consumption and promote natural resource preservation.

The rule system incorporates essential elements which include digital reporting and registration alongside a monitoring process that involves auditing and requires an implementation committee. The enforcement system will function effectively by solving possible problems that may occur. The "Polluter Pays Principle" shall guide enforcement by mandating compensation paid by manufacturers whose EPR targets remain unmet. Financial support from the collected funds will help manage uncollected batteries and non-recycled waste batteries. The Battery Waste Management Rules of 2022 provide a major stride toward environmental health improvement through proper battery waste management and recycling and reuse.

2. **Draft Battery Swapping Policy**

The process of battery swapping allows Electric Vehicles users to receive fully-charged batteries by exchanging their already-depleted ones. Battery swapping functions best as a charging solution for smaller 2-wheelers and 3-wheelers due to their smaller battery sizes. In February 2022, NITI Aayog began holding an inter-ministerial discussion to develop a draft policy for battery-swapping systems which would benefit EVs in India.

The proposed policy supports ongoing policy programs for EV promotion such as the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme and the Production Linked Incentive (PLI) scheme that already exist within the country. Battery swapping operates in India today and the number of swapping stations expands yearly. NITI Aayog maintains consistent interactions with battery swapping operators and manufacturers as well as vehicle original equipment manufacturers (OEMs), financial institutions, Civil Society Organisations (CSOs) and other expert groups to advance the sector. The battery swapping system adopted by India corresponds to global standards among dynamic EV battery ecosystems which feature numerous emerging technologies. The birth of a successful EV battery-swapping policy requires additional discussions among NITI Aayog alongside the Bureau of Indian Standards, the Department of Science and Technology, and other relevant departments to protect the technological advancement of the EV sector.

The information comes from Shri Nitin Gadkari who serves as the Union Minister of Road Transport and Highways and gave his response to the Rajya Sabha through written communication. [4]

3. **PLI Scheme for ACC Battery Storage**

[4] Battery Swapping Policy

On 12th May 2021, the Cabinet approved the National Programme on Advanced Chemistry Cell (ACC) Battery Storage through a budget of Rs. 18,100 crores. This scheme works to build India's Electric Mobility ecosystem and Battery Storage system through capabilities that focus on domestic production. New ACC manufacturing plants will be developed on a large scale through facilities that aim to increase domestic value while building the "Make in India" movement.

The scheme requires beneficiary companies to initiate a 25% domestic value addition that will escalate to 60% in five years. The investors must dedicate Rs. 225 crore per GWh of their initial capacity installation during the first two years. The scheme spans from January 1, 2023, through December 31, 2024, as the gestation period and then continues through the five-year performance period from January 1, 2025 until December 31, 2029.

[5]

B. United States

The recycling rules for LIBs are less strict in the USA as compared to regulations enforced within other countries such as those within the EU. The automotive sector maintains its dedication to developing a zero-emission transportation approach which requires adopting electric mobility. The United States saw 8.1% electric vehicle (EV) sales as a percentage of total light-duty vehicle purchases in 2024 starting from 2% in 2020. Through investments reaching over $515 billion during 2030, automakers will offer 130 electric vehicle models in the United States according to IHS Markit prediction.

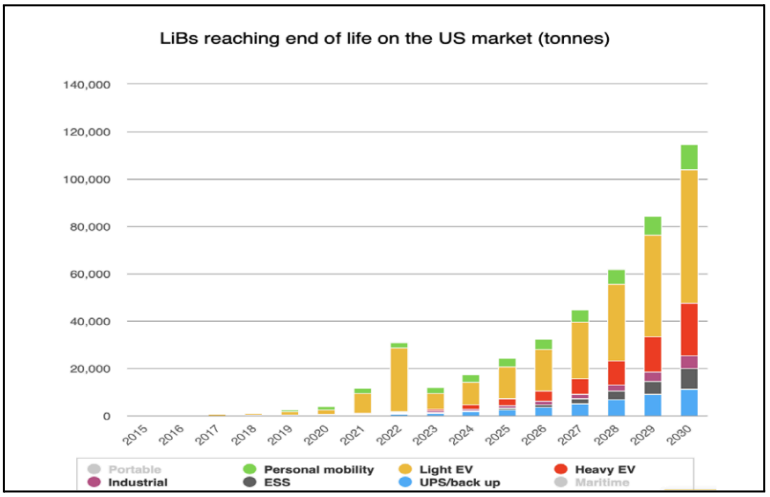

Image 2: Projected available lithium-ion tonnage for reuse and recycling by application in the United States. Courtesy of Hans Eric Melin of Circular Energy Storage.[6]

1. Federal Level Regulations:

[5] PLI scheme for ACC Battery Storage

[6] Projected available lithium-ion tonnage for reuse and recycling by application in the United States.

Bipartisan Infrastructure Law: The Bipartisan Infrastructure Law gives funding to develop electric vehicle battery recycling operations and implementation of second-life battery applications through research and demonstration activities. Through this law, the government backs research and development efforts to establish new methods to extract critical materials from discarded battery materials. Federal funding through the BIL exceeded $200 million to advance EV battery recycling and second-life applications in 2024 while the Department of Energy allocated $44.8 million for eight projects in October and the US government distributed $70.8 million that included $11.5 million specifically directed to state and local programs in November.

National Blueprint for Lithium Batteries: The Federal Consortium for Advanced Batteries developed the National Blueprint for Lithium Batteries to direct investments throughout the domestic battery manufacturing chain which seeks to establish clean energy production jobs in America. By 2030, the United States and its partners will establish a secure battery materials and technology supply chain that supports long-term U.S. economic competitiveness and equitable job creation, enables decarbonization, advances social justice, and meets national security requirements.[7] The long-term objectives outlined in this blueprint aim to eliminate cobalt and nickel in lithium-ion batteries by supporting processing R&D efforts and integrating recycled materials as a key component of a circular battery economy.

The Lithium-Ion Battery Recycling Prize: Functions as a competition which seeks to locate cutting-edge solutions between collecting, sorting, transporting and storing lithium-ion batteries resulting from electric vehicles (EV) together with consumer electronics, industrial, and stationary applications before they undergo recycling and materials recovery processes. The Lithium-Ion Battery Recycling Prize represents a $5.5-million staged competition that encourages American entrepreneurs to create financially viable processes able to capture 90% of U.S. spent lithium-based batteries for material recovery in the domestic supply chain.

2. State Level Regulations

California Assembly Bill 2832: The Department of Toxic Substances Control under California Assembly Bill 2832 must work alongside suitable stakeholders to develop plans for LiB EV battery recycling and reusing when their operational life ends.

Clean Cars 2030: Represents statewide legislation from April 15th 2021 to mandate electric power as the sole fuel source for all light-duty vehicles starting from model year 2030 onward. Washington secured its position as the first American state to implement a gas car ban through legislative measures and possesses the most advanced timeline for such a ban in the nation. New Jersey and New York adopted gas car bans shortly after California led the way with its announcement.

[7] National Blueprint for Lithium Batteries

Battery Stewardship Program: Lawmakers authorized this bill in 2023 to build a new state-wide used Battery recycling system. Washington residents benefit from the new battery recycling solution through a recycling program funded by battery producers who must carry out the recycling initiative for effective battery disposal.

C. China

A group from the University of Münster has been investigating how the demand for the three most important raw materials for batteries – lithium, cobalt and nickel – can be met entirely through recycling, in Europe, the US and China; in other words, when a completely circular economy will be possible in these regions. It concludes that China will achieve this first, followed by Europe and the US.

1. Policies for EV Battery Recycling in China

Botree Recycling: According to the World Economic Forum Reports, Botree Recycling stands as a Chinese start-up which has shown major success in battery recycling operations. The waste processing at Botree Recycling extracts essential minerals including lithium as well as nickel and cobalt through their patented low-price chemical procedures and battery dismantling operations. The refinements reach a point which enables the recycled minerals to be used again.

Extended Producer Responsibility: The Plan for the Implementation of the Extended Producer Responsibility System was issued by the State Council of China in 2016. Manufacturers must follow specified environmental obligations starting from production until their products reach final disposal according to this framework.

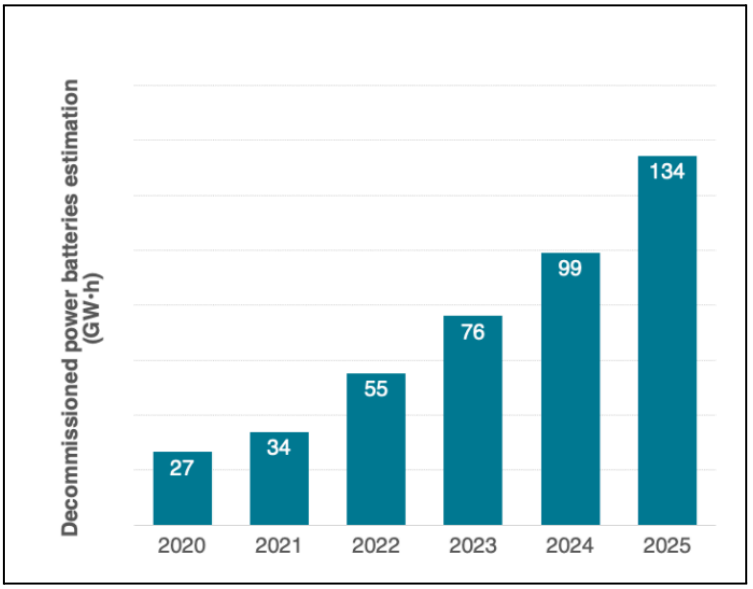

Image 3: The potential size of the EV battery recycling market in China. [8]

[8] The potential size of the EV battery recycling market

Battery Traceability System: China has established a national battery traceability platform, which tracks the lifecycle of batteries from production to disposal. It helps the country to keep track of the recycling process.

Pilot Program: The Ministry of Industry and Information Technology (MIIT) of China initiated the EV battery recycling program in 17 major Chinese cities in 2019. To accelerate battery recycling processes the pilot program encourages EV manufacturers to collaborate with battery producers vehicle dismantlers and battery second-use/recycling companies in creating regional collection and utilization networks across major regions and cities.

D. European Union:

The EU is experiencing a quick rise in EV battery marketplace demand. The global demand for EV batteries will grow 14 times by 2030 and the EU will command 17% of the total market share. Evolution in transport technology has become the main reason behind this trend. As battery demand increases the manufacturers need to reduce the environmental effects of raw materials they use because demand will match the raw material usage. Electric vehicles together with their battery manufacturing facilities have created an urgent need for an end-to-end battery recycling network within Europe.

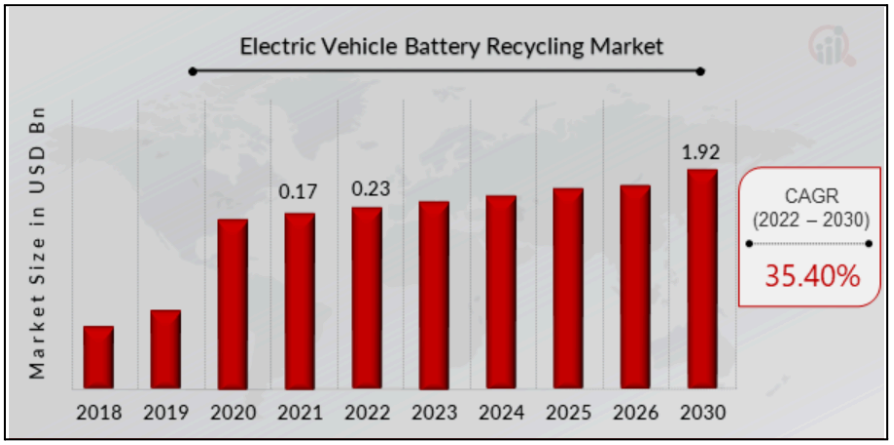

Image 4: EV Recycling Market in the EU.[9]

The EU Batteries Directive established regulatory control for batteries and waste batteries in 2006. Amendments were proposed by the Commission for this Directive in December 2020 because of evolving socioeconomic circumstances mixed with market trends technological improvements and battery application patterns.

1. Policies for EV Battery Recycling in the EU

[9] EV Battery Recycling Market in the EU.

EU Sustainable Batteries Regulation: The European Commission established an updated regulation for batteries and waste batteries through the EU Sustainable Batteries Regulation which received its enactment on July 12th 2023 with August 2023 as its effective date. The regulation seeks to establish common market guidelines which enable equal conditions for market competition and boost circular economic principles. The regulation targets environmental and social preservation throughout every life stage of the battery lifecycle. Various requirements regarding battery sustainability together with safety provisions and labelling standards emerged from the regulation. The policy establishes multiple targets regarding waste collection together with waste recovery and recycling operations

European Battery Alliance: The European Battery Alliance began operations in 2017 to construct a sustainable battery value chain that would both excel as a global competitor and guarantee the batteries required to power the transportation and energy sector decarbonization

New EU Battery Regulation: According to the regulation, the EU market must contain specified recycled content levels for each battery sold where cobalt stands at 16%, lithium at 6% and nickel at 6% in 2031. The regulation features battery collection requirements while requiring battery passport tracking for lifecycle data management.

The EU's Circular Economy Action Plan (CEAP): The policy represents an element of the European Green Deal. The initiative emphasizes sustainable battery recycling because it aims to reduce waste, maximize resource efficiency and support better product designs that lead to extended durability and ease of recycling. Through the CEAP Europe establishes the necessary recovery of critical raw materials from used EV batteries to decrease its dependence on imported raw materials from China.

IV. International Collaborative Initiatives on EV Battery Recycling

A. EU-India Initiative

The National Electric Mobility Mission Plan of India aims to reach 30% electric vehicle penetration among national vehicles in 2030. The fast-expanding EV market leads to pressing challenges regarding properly disposing of used lithium-ion batteries (LIBs) because these battery cells contain destructive materials like cobalt, nickel, lithium, and manganese. Dangerous environmental damage together with health risks emerge when these batteries are disposed of improperly.

India's generation of lithium-ion battery waste reached about 2,000 tonnes during 2022 but experts predict this number will surge significantly as more people adopt EVs throughout the coming decade. Lithium-ion battery recycling leadership among all nations belongs to the European Union since it implemented the EU Battery Directive to set LIB recycling standards and recovery requirements. Advanced EU recycling technologies enable the recovery of 95 percent of key materials from batteries which helps reduce the environmental impact of battery manufacturing as well as minimize resource waste.

The EU-India Clean Energy and Climate Partnership (CECP) acts as a foundation for their EV battery recycling collaboration by supporting mutual knowledge sharing and sustainable battery value chain development and technology transfer between partners. Through this partnership, India will develop a solid recycling infrastructure by drawing knowledge from EU experts who specialize in battery material recovery,

cycling management and regulatory standards. The initiative supports India's national objective to decrease reliance on imported raw materials like lithium, cobalt and nickel that are necessary for battery production. The alliance creates stronger positions for both regions to play in the worldwide markets of electric vehicles and renewable technologies.

B. Global Battery Alliance

In 2017, the Global Battery Alliance (GBA) was established as a public-private coalition to manage sustainable battery production methods and usage. The life-cycle of batteries serves as a key factor in the decarbonization of transportation and energy industries while creating environmental social and economic challenges.

The GBA seeks to build a sustainable battery value chain by leading the principle of responsible sourcing materials while lowering emissions levels and creating closed-loop systems for battery recycling by 2030. Since its establishment in 2022, the Global Battery Alliance has grown to incorporate more than 170 members including Tesla in addition to automobile manufacturers like BMW and material supplier Umicore as well as institutions representing governmental and United Nations programs.

The Battery Passport is a GBA initiative that streams battery activities from mining materials through production and EV and storage uses. Through their system, the GBA maintains supply chain accountability because it tracks environmental consequences and human rights effects with a special focus on the Democratic Republic of Congo's cobalt mining which faces criticism for its unsafe work conditions.

The total global demand for lithium is divided equally between batteries at 60% while batteries consume 30% of the cobalt market[10]. The International Energy Agency projects battery demand will surge 19 times over from 2030 until the expansion of EVs and renewable energy storage systems. Through its work, the GBA promotes battery recycling innovation while reducing production GHG emissions and upholding labour practices.

The Global Battery Alliance functions as the essential force that harmonizes industry partnerships and policy implementation to develop an ethical sustainable battery supply chain system during increasing global demand.

C. Green Li-ion

Green Li-ion started in Singapore in 2020 as a startup dedicated to developing sophisticated battery recycling solutions concentrating on lithium-ion batteries (LIBs). The company pursues solutions to handle growing waste from electric vehicle (EV) batteries and electronic devices because both items are central to achieving clean energy transition. The increasing demand for batteries has made recycling necessary to lower environmental consequences and decrease dependency on finite raw materials such as lithium, cobalt and nickel.

The company created multi-cathode recycling technology which distinguishes itself from typical battery recycling methods. Current standard battery recovery methods succeed in regaining only 40-50% of the materials while extracting minimum key components. The recycling technology of Green Li-ion enables the complete recovery of 95% of LIB materials starting from the essential components including cathodes and

[10] Global demand for Lithium

anodes as well as electrolytes. The combination of this method creates a loop for battery manufacturing which decreases waste output while cutting down on raw material mining needs.

Green Li-ion states its recycling machine GLMC-1 generates battery-grade materials such as cobalt and nickel sulfate within 24 hours which exceeds traditional recycling periods of weeks. Research shows that the recycling techniques developed by Green Li-ion decrease battery recycling carbon emissions by 85%. Green Li-ion technology resolves a critical need for green battery management because experts predict lithium demand growth will surge 42 times during the next twenty years. Green Li-ion collaborates with different industrial players spanning electric vehicle makers to energy storage companies to expand its technology worldwide. Green Li-ion implements innovative solutions that link to circular business models because their process helps preserve the environment while decreasing extraction costs and creating sustainable battery systems for future use.

V. Challenges

The main obstacle to recycling EV batteries is the expensive process of recovering their materials. The extraction of lithium and cobalt together with nickel and manganese from lithium-ion batteries (LiBs) proves expensive and difficult to manage. The expenses of battery recycling exceed the market value of recovered materials by up to $2000-$3000 per ton in U.S. facilities making it unprofitable without government support. The World Economic Forum reports (2022) that lithium-ion battery recycling worldwide stands at a mere 5% resulting in extensive environmental dangers.

EV battery recycling faces challenges due to a poor built-in system for battery waste management. The increase in electric vehicle usage throughout India has not led to sufficient development of advanced recycling centres across the nation. The projected quantity of retired EV batteries in India for 2030 stands at 70 GWh and current recycling capability remains under capacity. The complete absence of mandatory regulations regarding LiB collection and storage alongside recycling operations makes the situation worse. The Battery Waste Management Rules introduced by India in 2022 face difficulties in executing their intended objectives.

Improper battery waste disposal has serious negative effects on the environment. In 2022 the world had available 105,000 tons of battery materials for recycling but production scraps accounted for nearly all materials which were ready for recovery. The improper discarding of banned items causes environmental damage because the International Energy Agency (IEA) predicts that batteries drive 60% of global lithium usage together with 30% of cobalt utilization.

The EU-India Clean Energy and Climate Partnership and Global Battery Alliance initiatives along with other entities work to solve these issues through recycling framework establishment and policy collaboration with a focus on innovation development. Additional infrastructure development coupled with economical recycling technologies stands as the main obstacle to the widespread implementation of these initiatives.

VI. Recommendations

The following suggestions must be implemented to improve both the sustainable nature and service quality of electric vehicle battery recycling operations:

A. Strengthen International Collaboration: The growth of international alliances between the Global Battery Alliance and the EU-India initiatives requires further development to enhance knowledge-sharing of technology and best practice exchange. Laboratory partnerships between countries enable entities to maximize collective strengths for improved recycling methods and facilitate the resolution of mutual obstacles including material retrieval and regulatory compliance.

B. Invest in Advanced Recycling Technologies: It is suggested that both governments and private businesses dedicate increased financial support to explore new recycling technology developments. The refinement of pyro-hydro processes needs to occur to lower operational expenses and energy usage since these methods extract lithium and nickel together with cobalt efficiently. Through combined public and private funding of these technologies, the industry can advance its sustainable operational methods.

C. Promote Extended Producer Responsibility (EPR): Harmonize Global Regulations: A standardized framework of global regulations that pertain to EV battery recycling must be established to build a unified efficient supply chain. Standard recycling policies will help manufacturers follow single procedures for scrapped battery management which creates border-to-border accountability for waste disposal and streamlines international company operations.

D. Extended Producer Responsibility (EPR) needs global expansion with enforced programs which make manufacturers responsible for single-use product lifecycle management. Companies should receive financial benefits for battery manufacturing with recycled materials alongside comprehensive strategies for collecting used batteries while establishing their repurposing process. These measures support sustainable EV sector operations.

E. Raise Public Awareness: A comprehensive points-based system can be established as part of awareness campaigns which can be conducted in electric vehicle (EV) showrooms and battery recharge stations. This initiative aims to educate customers by providing them with valuable information on how to properly recycle batteries and the significant environmental benefits associated with doing so.

VII. Conclusion

A complete shift towards electric vehicles is a crucial step for minimizing carbon pollution while resolving environmental issues. Electric vehicle batteries specifically lithium-ion have life cycles that present major operational difficulties for the industry. The correct recycling process of batteries remains essential because it protects the environment and supports sustainable resource management of cobalt, nickel and lithium. Global recycling operations remain under development at present. The leading nations in electric vehicle battery recycling include China together with the European Union and the United States through their coordinated policies, technological innovations and collaborative partnerships. Large-scale implementation of EV battery recycling is held back by both expensive recycling costs along with sparse advanced infrastructure and inconsistent worldwide regulatory standards. Almost all current recycling infrastructures concentrate on

processing manufacturing waste yet fail to handle EV batteries at the end of their life cycle which underscores the importance of investing in recycling platforms.

The advancement of EV battery recycling depends on substantial financial support to enhance recycling technologies particularly those based on pyro-hydro processes. The efficient extraction of valuable materials from used products requires public and private entities to develop affordable green extraction techniques. A circular economy requires extended producer responsibility policies alongside financial incentives to businesses operating in the recycling sector which promotes effective material recycling of used batteries.

Furthermore, global collaboration is key. The Global Battery Alliance among international partners should strengthen efforts to exchange knowledge about regulations and standards. Effective educational programs for the public about proper battery recycling and disposal methods must be developed because consumers and businesses need to understand their recycling duty.

EV battery recycling, under proper policies, investments, and international alliances, can lead to substantial environmental benefits that protect resources while enabling the electric vehicle industry's sustainability.

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