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A 6R-Based Circular EV Battery Supply Chain in India: Technology Roadmap and Insights from MaxVolt ReEarth

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Abstract
With the rise of EV adoption, significant changes occur in the transportation industry; however, it also generates additional pressure on natural resources and identifies gaps within current EV battery supply chains that should be addressed. The supply chains are currently linear, focusing on the extraction of raw resources, their processing, usage, and disposal and recycling, which creates sustainability issues. This paper presents a technological roadmap of 6 R (reduce, reuse, repair, refurbish, remanufacture, recycle) that aims at developing an innovative model that will ensure a transition to a circular EV battery supply chain. Contrary to popular recycling-based solutions, the proposed approach is focused on retaining resources and prolonging their lifecycle through various measures such as reuse, repair, and remanufacturing. Furthermore, the paper provides information about other approaches and business models that may help in the transition to circular EVs. For example, this includes the application of various policies such as extended producer responsibility and requirements concerning recycled content. The findings indicate that the use of a more complex approach that incorporates all aspects of circular economy may lead to positive outcomes regarding reducing negative impacts on the environment, dependence on virgin resources, and promoting sustainable development.
Keywords: *Circular economy, EV batteries, 6R framework, battery recycling, sustainable supply chain, critical minerals.*

1. INTRODUCTION

The ongoing shift towards sustainability in the mobility sector has led to an increasing focus on EVs as a promising technology that enables the reduction of GHG emissions and fossil fuel dependency. As the climate agenda gathers support among governments, industries, and citizens alike, EV promotion becomes one of the mainstays of decarbonization strategies. Yet, the expansion of the EV market also gives rise to numerous difficulties associated with sustainable procurement of battery components, especially because of their high demand for critical resources like lithium, cobalt, nickel, and graphite [1]. Traditionally, the flow of materials within EV battery supply chains operates on the principles of a linear economy, meaning that the process involves extracting natural resources, manufacturing components, using products, and discarding waste. The existing "take-make-dispose" paradigm leads to massive resource depletion, environmental degradation and generation of waste streams. Furthermore, the geopolitical concentration of critical minerals poses additional risks in terms of ensuring secure supplies of materials at stable prices, particularly for developing countries like India [2].

The idea of circularity can be seen as a plausible solution for the existing problems with linear systems. The circular EV battery supply chain is oriented towards efficient use of resources through lifecycle extension, resource recovery, and waste minimization. Although recycling has long been considered the key pillar of any circular model, it fails to deliver on its promises owing to high energy input and inefficiency. Hence, there is a need for a different path towards sustainability, which involves other methods preceding recycling. The implementation of the 6R principle i.e. Reduce, Reuse, Repair, Refurbish, Remanufacture, and Recycle is a way forward toward transitioning to circularity [3]. This approach makes it possible to implement several loops of high-value resource retention before engaging in waste management and recycling practices.

The emergence of advanced digital technologies like artificial intelligence, Internet of Things (IoT), and blockchain is another step towards the implementation of a circular economy, as they can help in monitoring, maintenance and material traceability. In addition, innovations in the area of battery materials and manufacturing processes facilitate recyclability and eliminate dependency on rare minerals [4].

The main purpose of this paper is to create a comprehensive 6R technology roadmap for EV batteries' circular economy. The current obstacles will be identified, and the potential enabling technologies will be considered. Finally, a holistic approach towards creating an efficient circular economy will be proposed [5]. This work focuses on moving beyond the current perspective on waste disposal towards resource recovery and optimization in battery lifecycle. Finally, the circularity of electric vehicle battery value chains cannot be viewed as a necessity for the environment alone, but rather as an imperative for economics and strategy. Circular processes must be designed in collaboration with various stakeholders, ranging from manufacturers to policymakers to academics to recycling facilities, in order to turn waste into wealth [6].

2. Linear vs Circular EV Battery Supply Chain

The linear chain operates through the conventional "take-make-use-dispose" cycle. Materials are extracted, processed, then disposed of after being utilized. This is how most industries have operated historically, including the early production processes for electric vehicle batteries [7].

2.1Linear EV Battery Supply Chain

The linear supply chain operates under a conventional "take-make-dispose" paradigm, which involves extraction of materials from the earth's crust, use them and disposal as waste. The conventional linear process works well in industrial systems but not necessarily when it comes to EV batteries. In the linear cycle, mining is done to extract raw materials like lithium, cobalt, nickel, and graphite. The raw materials are transported to undergo processing and conversion into battery chemicals. Subsequently, the processed and refined products are transported to battery manufacture [8].

During the utilization stage, the battery will operate in the electric vehicle for 6 to 8 years, depending on the level of operation and battery chemistry. The battery can continue operating until its condition deteriorates beyond usability (typically less than 70%-80% State of Health). After this point, it is considered to have reached its end of life (EOL). Such an approach creates significant problems, including:

- The depletion of natural resources caused by constant harvesting
- Deterioration of the environment from resource extraction and disposal
- Waste of valuable resources, as few components are usually recovered
- High costs associated with the need to extract new materials

Linear process is ineffective and unsustainable when viewed in the context of the forecasted rapid increase in electric vehicle usage [8].

2.2 Circular EV battery supply chain

The circular supply chain takes the linear approach of recycling and replaces it with the closed-loop supply chain that optimizes resources, increases battery longevity, and allows the extraction of valuable materials [9]. While the mining and manufacturing stages remain, starting from the design itself, the batteries are made circular through the use of modularity, ease of disassembly, and low-hazardous contents.

Following the usage stage by vehicles, the batteries are collected rather than disposed of and are transported in reverse logistics to an evaluation center were based on SOH, the batteries take different routes-

- Second Life/Reuse Utilization: The battery is refurbished to be used in more forgiving applications like, Energy storage systems for renewable energy generation (e.g., solar and wind), Grid balancing applications and Battery storage for back-up power.
- Recovery/Recycling: The batteries that cannot be reused are recycled using high-end recycling techniques (including mechanical recycling, hydrometallurgy, and direct recycling) to extract metals like lithium, cobalt, and nickel.

The recycled materials are then reintroduced to the production process of batteries, making it a circular system.

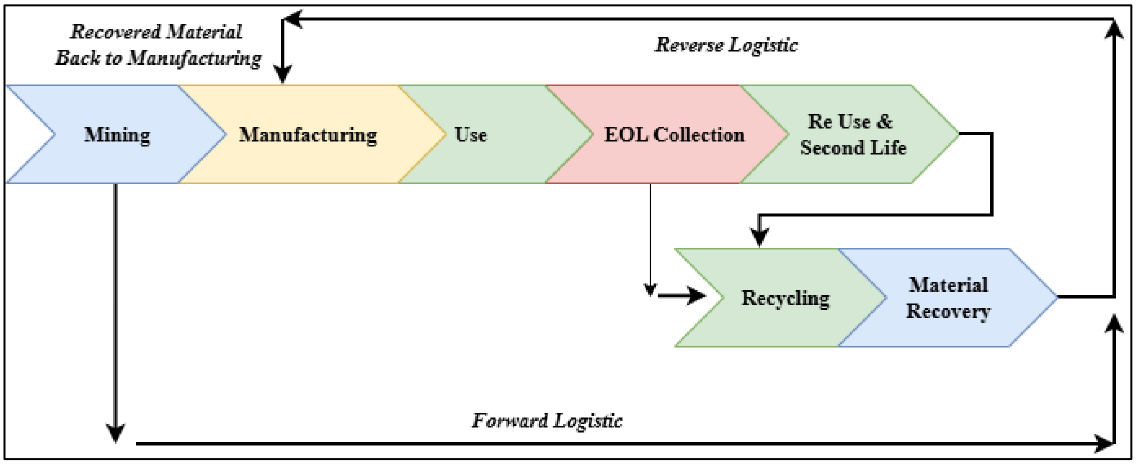

Figure 1: Circular EV Battery Supply Chain

3. The 6R Framework for EV Battery Circularity

The 6R framework includes Reducing, Reusing, Repairing, Refurbish, Remanufacture and Recycling, which builds on the 3R theory to create a sustainable way of living and circular economy through waste reduction. The core ideas involve lowering consumption, extending product longevity and ensuring the appropriate disposal of materials to prevent excessive reliance on landfills [7].

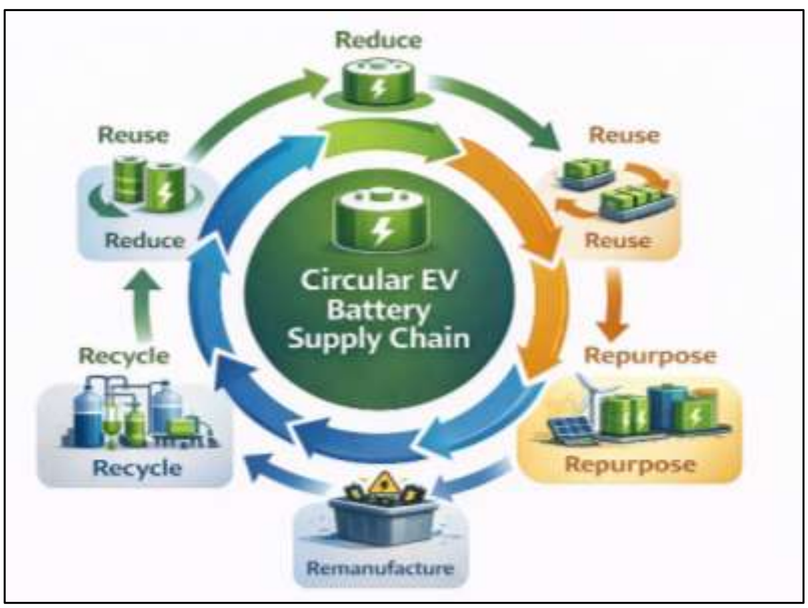

Figure2: 6RFramework for EV Battery Circularity

The figure 2 illustrates the EV Circular Battery Supply Chain using the 6R framework, a sustainability strategy that keeps battery materials in continuous use while minimizing waste and environmental impact.

3.1*Reduce: Design for Circularity*

The objective of reduction is to minimize material use and impact during design and production. Breakthroughs in battery technology, such as using low or no cobalt cathodes (like LFP or solid-state batteries), would lessen the reliance on critical minerals. Material savings can also be achieved through light weight battery design, energy efficiency and more efficient manufacturing methods [8]. Digital technologies, such as

AI-powered design optimization and life-cycle assessment (LCA), can help manufacturers recognize opportunities to optimize material use and minimize waste.

3.2Reuse: Second-Life Applications

Reuse is concerned with reusing batteries after their end-of-life use as an EV battery. They can be reused in other applications like stationary energy storage, where lower requirements on energy density than those in cars will allow them to serve another purpose despite being too old to be used in the automotive sector. Second-life application requires standardized testing and battery diagnostics. The creation of digital battery passports is one of the emerging solutions to improve this area [9].

3.3Repair: Component-Level Restoration

The repair approach emphasizes enhancing the lifespan of batteries by carrying out maintenance and repairing faulty parts. With modular batteries, there are easier ways to access different cells or modules and make repairs without the need to replace the entire battery pack [10]. With advanced diagnostics tools like AI-powered fault identification and monitoring, identifying wear patterns will guide the required maintenance measures. The approach does not only reduce wastage but also cuts down costs in the long run for EV users.

3.4***Refurbish: Performance Restoration***

The process of refurbishing entails the repair of used batteries to restore their usability by cleaning and rebalancing them while replacing some of their parts. The batteries that have undergone refurbishing are sold back to the market in areas where there is no high demand. With automation and robotics becoming common in the process, it is crucial to set quality benchmarks.

3.5Remanufacture: Industrial Rebuilding

Unlike refurbishment, remanufacturing involves dismantling the batteries and reconstructing them either as they were initially manufactured or better with both new and reclaimed parts. In this case, it involves advanced disassembly techniques, effective sorting of the materials used, and high-quality assembly skills [11]. Remanufacturing will help to cut back on virgin materials while at the same time achieving high standards of production. Remanufacturing promotes the creation of a secondary market for battery components.

3.6***Recycling: Material Recovery***

Recycling is the last step in the 6R hierarchy of actions towards battery waste management and serves as a method of extraction of the materials used in batteries after their life cycle. There are two main recycling approaches used in batteries pyrometallurgy that includes smelting and hydrometallurgy based on chemical leaching. Direct recycling that helps reclaim the cathode material without additional procedures is an innovation in the field [12].

Table 1: R strategy with their value retention levels

R Strategy	**Objective**	**Value Retention Level**
Reduce	Minimize raw material use, energy consumption, and waste during design and production	▧ Very High (maximum value retained, minimal loss)
Reuse	Use the product again without major modification	▧ Very High
Repair	Fix faults to restore functionality	▨ High

Refurbish	Improve or upgrade performance by replacing worn components	▨ Moderate to High
Remanufacture	Rebuild product to like-new condition using old components	▨ Moderate
Recycle	Recover raw materials from end-of-life products	▧ Low (value reduced to material level)

The above table 1 showing the six R strategies employed in circular economies for EV battery packs based on their value preservation over the life-cycle. The strategies are usually ranked from the strategy that retains the most value (highest rank) to the one that retains the least (lowest rank), the sooner you act, the more value retained [12].

4. System Architecture of 6R Circular EV Battery Supply Chain

The system architecture of a 6R-based circular EV battery supply chain is a complex, hierarchical structure aimed at improving the efficiency of resource use, increasing battery lifespan, and minimizing ecological footprint. Unlike linear models, this system combines supply chain functions with reverse logistics and value creation activities, allowing for repeated reuse of materials and energy within the battery cycle. Overall, the proposed architecture involves three interrelated levels and one digital level. All layers work together in an interconnected manner using information and material exchange [13].

- Forward Flow Level (Production and Utilization)
- Reverse Flow Level (Recycling)
- Circular Value Creation Level (6R Cycles)
- Digital Integration level (AI, IOT, Blockchain)

4.1Forward Flow Layer (Reduce-Oriented Design and Production)

Forward Flow Layer is the starting layer for the 6R circular EV battery supply chain, which covers the sourcing of raw materials, battery designs, manufacture, and usage phases. In the context of the circular economy, this layer has been designed such that its focus is on the Reduce part of the 6R process where the objective would be to reduce the consumption of resources, minimize any negative impact to the environment, and cost.

The center of gravity within the forward flow process is the Design for Circularity (DFC), whereby sustainability principles are incorporated within the design of batteries. Besides improving performance, it aims at making batteries more reusable, repurpose, remanufacture and recyclable. Forward flow layer Design approaches include:

- Use of High Energy Density Materials to Reduce Weight
- Low Dependency on Critical Materials such as Lithium Iron Phosphate (LFP)
- Modular Design for Ease of Separation
- Non-Hazardous Material Use for Simplification of End-of-Life Disposition
- Batteries can be designed with efficient chemistry (LFP, low cobalt NMC batteries).
- Lightweight and modular design reduces material consumption.
- Energy-efficient manufacturing that avoids generating any waste.

Through adoption of the above principles, the flow process manages to minimize the use of input materials as well as streamline future processes. The emphasis of this layer on material efficiency and sustainable production provides the necessary base for creating an effective regenerative chain [14]. All of the downstream activities depend significantly upon the decision made in this phase, which makes it the most vital point to enter circularity.

4.2 Reverse Flow Layer (Collection and Logistics Network)

This is a vital layer within the 6R circular EV battery supply chain that takes care of the recovery of end-of-life (EOL) batteries from the market and directing them towards the right channels for retaining value. While the forward flow process is relatively simple and easy to predict, the reverse flow process is rather complicated, random, and condition dependent. The performance of this layer plays a critical role in determining whether the reuse, repurpose, remanufacture, recycle, and recover processes can succeed. The main purpose of this layer is to:

- Close the loop between usage and resource recovery
- Assure the proper handling and transportation of batteries
- Sort and direct towards 6R processes

As soon as batteries reach their end of life, which occurs at a certain State of Health (SOH; usually 70–80%), they become part of reverse logistics, such batteries are sorted according to below conditions:

- Good SOH => Reuse/Repurpose
- Medium SOH => Remanufacturing
- Bad SOH => Recycling

Reaching this stage involves- Internet of Things (IoT)-based monitoring, Artificial intelligence (AI)-enabled sorting technologies and Battery passports. This ensures effective routing through the proper 6R pathway [5].

4.3 Circular Value Retention Layer (6R Loops Integration)

The Circular Value Retention Layer constitutes the backbone of the 6R circular EV battery supply chain, in which batteries are subjected to several pathways to achieve the highest possible value extraction. Whereas conventional systems end their life cycles with disposal, the circular value retention layer comprises six feedback loops i.e. reduce, reuse, repurpose, remanufacture, recycle, and recover that retain various forms of value throughout the system's life cycle. These loops aim at postponing, reducing, or even preventing waste generation while maximizing the utilization of each battery until its material value can be recovered.

The hierarchy design is such that all "R" indicates levels of priorities for retaining values in the architecture. At any point, value is always retained at a maximum possible loop because the more loops the higher amount of embodied energy, materials integrity, and economic value. The flow from one loop to another loop is determined by factors such as battery SOH, SOC, resistance and degradation rate. Their benefits accrued through such integration include Batteries' cascaded usage, Minimal loss of resources at every level and Optimization of lifecycle extension [16].

4.4 Digital Integration Layer (AI, IoT, Blockchain)

The Digital Integration Layer forms the core intelligence that transforms the 6R Circular EV Battery Supply Chain to become a data-centric cyberspace ecosystem. While the forward and reverse flow layers involve the physical movement of materials and batteries within the supply chain, the digital integration layer takes care of the information flow and decision-making for the entire lifecycle of the process. With the implementation of state-of-the-art technologies like AI, IoT and Blockchain technology, the supply chain is made to be more visible and controllable at all times. To begin with, a key function performed by this layer is that of providing complete visibility regarding all stages of the battery's lifecycle from its production and utilization up to collection and incorporation back to the cycle again. It means that all processes will be constantly monitored, analyzed, and optimized, which helps route each battery into the appropriate 6R pathway [17]. Otherwise, a lack of visibility leads to inefficiencies and improper classification of batteries within the closed-loop cycle, reducing the circular economy potential.

One more important purpose served by this layer is related to intelligent decision-making for value retention. Based on sophisticated analytical and predictive tools and models applied to SOH, depreciation rate, economic considerations, among others, the system decides when to reuse, repurpose, remanufacture, or recycle a given battery. In this way, the entire life cycle of batteries can be optimized, ensuring their maximum possible value and minimum wastage. To put it briefly, the digital layer serves as a smart engine responsible for the flow of materials in a circular economy. Finally, the Digital Integration Layer guarantees the traceability of batteries, which is necessary for compliance with legislation and other requirements [18]. Indeed, a multi-stakeholder ecosystem with manufacturers, recyclers, logistics companies, and legislators involved requires

proper traceability systems and processes. Data about the battery origin, chemical composition, owner, and other relevant facts are collected throughout the entire life cycle. Such information is needed to comply with environmental regulations, including Extended Producer Responsibility, and avoid any illegal operations.
This layer increases the operational efficiency of the system through constant performance evaluation and optimization of inefficiencies within the processes. Real-time changes in logistics, processing, and routing become possible, which decreases costs and optimizes resource allocation. For instance, predictions can lead to improved collection timings, shorter distances in transportation, and minimized processing times, making the entire system more efficient and economically sustainable. The Digital Integration Layer is responsible for enabling the move towards an automated and optimized circular ecosystem. The incorporation of technologies like artificial intelligence, Internet of Things, and blockchain technology allows for automated decision-making, distributed collaboration, and data exchange. This not only ensures scalability but also flexibility within the circular supply chain, allowing it to respond to varying conditions, including increased demand for batteries, higher raw material prices, and new regulations.

5. Implementation 6R in MaxVolt Energy & ReEarth

The company MaxVolt Energy has employed a circular approach in its operations through vertical integration of the manufacturing process and the recycling process through its subsidiary MaxVolt ReEarth. In essence, MaxVolt Energy endeavors to establish a lithium battery loop through the tracking and recycling of batteries that have been used for different applications. The circular business approach employed by MaxVolt Energy can be considered a practical example of the application of the 6Rs framework in business.

5.1 Refuse: Reducing the Dependence on Primary Resources

The "Refuse" concept implies a reduction in dependence on primary raw material extraction and imports of virgin materials, mainly lithium and cobalt. Hence, the emergence of the very idea of creating MaxVolt ReEarth demonstrates a company's desire to replace virgin materials with recycled ones. Through the development of a technology, which reprocesses recovered metals back into batteries, the company makes efforts not to mine the earth but to recycle what has been mined.
That is why using the "Refuse" concept is an excellent tool for reaching India's goals of resource security and reducing environmental damage associated with mining practices.

5.2 Reduce: Resource Efficiency and Environmentally Friendly Practices

In relation to the Reduce concept, MaxVolt Energy works toward minimizing the environmental impact of battery production. Thus, at the manufacturing level, it emphasizes the importance of reducing greenhouse gas emissions, waste formation, and energy consumption. Furthermore, during the recycling process, ReEarth uses hydrometallurgy and mechanical processing, which do not have a huge footprint due to high temperatures. Besides, using smart battery technologies helps to reduce battery failures, thus ensuring efficient material throughput.

5.3 Reuse: Second-Life Uses of Batteries

"Reuse" is another essential element in the MaxVolt circular business model. In particular, MaxVolt ReEarth integrates second-life applications into its operations directly. Used EV batteries with enough capacity left are utilized for:

- Stationary energy storage applications
- Integration of renewable energy sources (solar/wind storage)
- Backup power supply for telecom operators

This measure helps increase the lifecycle of batteries while delaying their entry to the recycling process, allowing for further economic exploitation. It may open up new business prospects in terms of energy storage, too.

5.4 Repair: Increasing the Lifetime of Batteries via Interventions

MaxVolt Energy operation is designed in such a way that allows it to support "Repair" principles via its modular battery structure and lifecycle management measures. By facilitating proper diagnostics and careful disassembling of batteries, the company provides means for-

- Module or porting materials replacement within battery packs
- Refurbishment of partially damaged battery packs
- Balance restoring
- BMS repairing (Communication & connection)

These actions lead to minimizing waste production and increasing the lifetime of batteries before they need to be recycled or reused.

5.5 Remanufacture: Reworking of Battery Systems

Remanufacturing is intrinsic to the mid-life cycle segment in the MaxVolt system. If batteries cannot be reused, they undergo a process of disassembly, inspection, and rework. MaxVolt takes care of-

- Disassembly and shredding of batteries
- Sorting and categorization of battery components
- Reworking of viable modules into working packs

In effect, this allows the company to refurbish batteries to their original capacity for use in other applications.

5.6 Recycle: Circular Economy

The most developed form of circular economy is demonstrated in the Recycle/Recover stage with a prominent role played by MaxVolt ReEarth. The firm has designed a comprehensive recycling cycle that entails Disassembling and breaking down batteries at the end of their life, Generation of “black mass” and Extraction of important minerals like lithium, cobalt, nickel, and manganese. Maxvolt use the hydrometallurgical extraction techniques ensures-

- Higher efficiency in recycling
- Less negative impact on the environment
- Decreased amount of landfill waste

In addition, direct lithium recycling technology may be used to increase recycling efficiency and simplify the process. The extracted minerals are reintroduced to the production cycle for the creation of new batteries.

5.7 Integrated 6R Circular Model in Action

MaxVolt Energy and MaxVolt ReEarth are examples that show the practical application of the 6R framework in industries. The MaxVolt approach underscores the significance of vertical integration, recycling technology, second life ecosystem and policy and industry cooperation. The integrated activities of MaxVolt constitute an integrated 6R strategy as follows-

- Upstream (Refuse, Reduce) - Sustainable design and minimum raw materials usage
- Midstream (Reuse, Repair, Remanufacture) - Extended lifecycle and retaining value
- Downstream (Recycle/Recover) - Material recovery and reincorporation

The process of integration will ensure batteries continuous presence in the value stream to extend their lifecycles and transform the linear model into a closed loop circular supply chain model. It serves as a realistic template that can be adopted by developing nations such as India, which are witnessing a fast transition towards electric vehicles (EV).

6. **Integrated Technology Roadmap (2025–2040)**

The move towards adopting a circular economy approach in the EV batteries value chain demands a strategic plan that covers a period of several decades and takes into account aspects such as technological advancement, infrastructural development, legislation and market dynamics. The adoption of 6R approach (Refuse-Recycle) is carried out through three different phases; Foundation (2025-2030), Scaling (2030-2035), and Optimization (2035-2040).

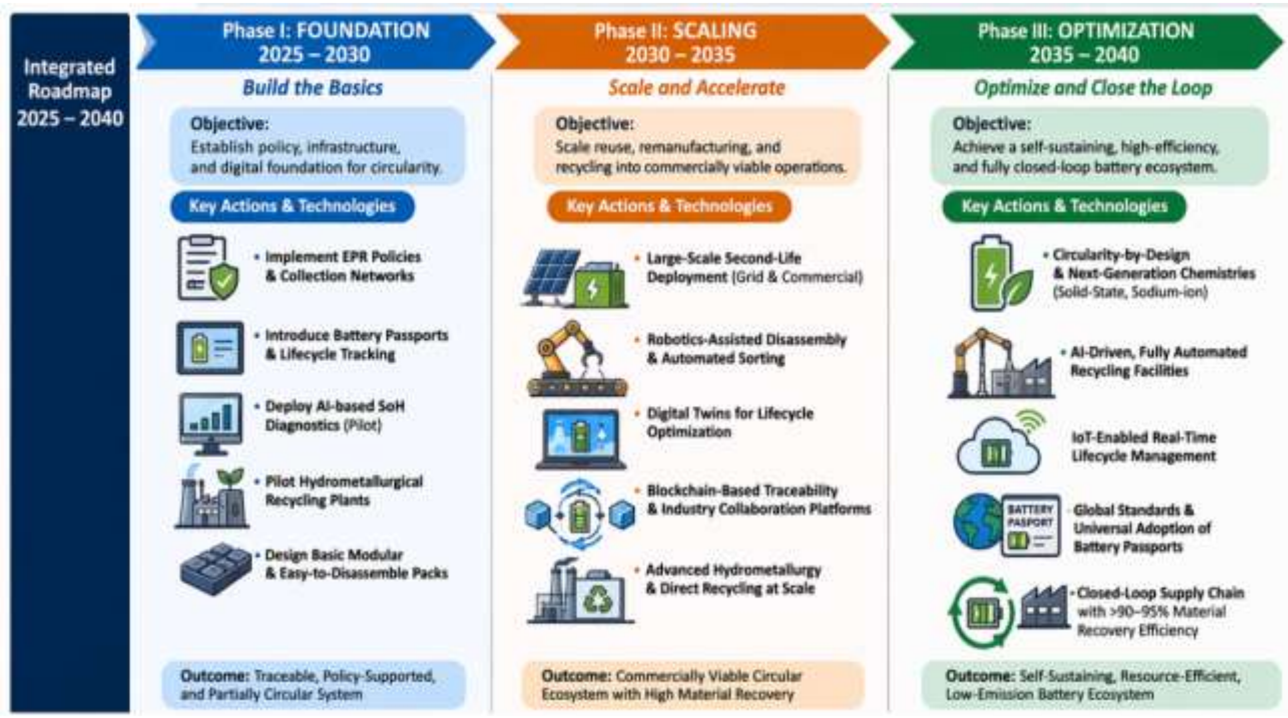

Figure 3: Integrated Roadmap 2025-200

6.1Phase I (2025-2030): Foundation and Ecosystem Development

The first stage is aimed for creating the essential ecosystem that would foster the circular nature of the EV battery value chain. At this stage, the efforts by both government bodies and industry players are geared towards developing proper collection and reverse logistics systems that would direct used batteries into the recycling system. Regulations like Extended Producer Responsibility are enforced to ensure accountability in terms of battery lifecycle management among producers. In addition, the battery passports make it easy to trace and monitor battery composition and ownership. On the other side, there is a steady implementation of principles of circularity in designing batteries such as modularity and standardization of battery packs. The beginning of investments in recycling systems is observed in favor of hydrometallurgy, which is seen as more efficient in recycling batteries compared to pyrometallurgy [19]. Although economically viable investment is still hard to achieve, subsidies may be needed to facilitate investments in recycling technologies.

Additionally, pilot projects on secondary life uses such as stationary batteries become more popular. Collaboration initiatives by industry players are developed to explore business models, while digitalization through BMS becomes increasingly common in collecting relevant lifecycle data. Phase I sets up the infrastructure needed for circularity in the battery industry.

6.2Phase II (2030-2035): Scaling & Industrial integration

The second stage involves scaling up from pilot projects to full-blown industrial adoption. This is where a considerable number of batteries of electric vehicles reach their end-of-life point, which presents both a problem and an opportunity for value extraction. Established reverse logistics systems guarantee that these batteries are collected and transported to specialized centers effectively. Automation and robots play a pivotal role in the disassembly process, leading to substantial cost savings and enhanced safety, especially in managing toxic battery parts. The markets for second-life batteries also grow exponentially due to advances in the estimation of state-of-health using artificial intelligence technologies. Batteries not suitable for use in electric cars undergo repurposing for energy storage applications such as microgrids, stationary storage, and backup power. Remanufacturing becomes economically feasible as well due to modular batteries.

In addition, there is an improvement in the technologies used in recycling, with better efficiencies in terms of the amounts of materials recovered from electronic waste. Hybrid recycling technologies, which combine hydrometallurgy and direct recycling techniques, become common at this stage, where not only the raw materials but also the cathode materials are recovered without compromising their quality. From an economic perspective, the circular economy model gains more prominence as recovered materials start compensating for the cost incurred in extracting virgin resources. There is also a high degree of cooperation between automobile manufacturers, recyclers, and energy companies, leading to the establishment of industrial ecosystems [20].

6.3Phase III (2035-2040): Optimization & Close loop Circularity

This stage is characterized by the maturity and refinement of an EV battery supply chain that is wholly circular. At this point, circularity has been firmly integrated into all aspects of the battery system, including its design, production and management through its lifecycle. The batteries have been designed to be highly recyclable, modular and easy to recover. They produce minimal waste, making end-of-life processing more straightforward. Recycling becomes efficient (often above 90%) due to the adoption of technologies such as direct cathode recycling and low energy extraction. Digital twins and lifetime monitoring contribute to maintenance and optimized use, while transitioning between phases becomes smoother. Resource efficiency becomes nearly optimal, and there is minimal reliance on primary material sources.

The notion of waste is totally erased in this phase through the systematic recycling of used batteries back into the production process as secondary sources of materials. Digital technologies based on artificial intelligence (AI) and big data analytics create transparency along the entire supply chain, which allows for the optimization of material flows, demand forecasting, and lifecycle management [21]. From a regulatory standpoint, worldwide standardization facilitates conformity and compatibility among countries. Business models like Battery as a Service (BaaS) are adopted as a norm, changing the mindset of owning a product to maximizing its value throughout its lifecycle. The end result is that Phase III will be a closed-loop cycle in which EV batteries are continually cycled in the economy, symbolizing the shift from waste to resource

Table 2: Integrated technology roadmap 2025-2040 summery

Dimension	Phase I: Foundation (2025–2030)	Phase II: Scaling (2030–2035)	Phase III: Optimization (2035–2040)
Primary Focus	Infrastructure & policy setup	Industrial scaling	System optimization
Battery Volume (EoL)	Low–moderate	High	Very high
Design Strategy	Basic modularity	Standardized modular design	Circularity-by-design
Reuse (2nd Life)	Pilot projects	Large-scale deployment	Fully integrated markets
Repair & Remanufacture	Limited	Growing adoption	Highly optimized
Recycling Technology	Pilot hydrometallurgy	Advanced hydro + direct recycling	High-efficiency closed-loop
Material Recovery Rate	50–70%	70–90%	>90–95%
Digital Technologies	Battery passports, basic AI	Digital twins, blockchain	Fully AI-integrated lifecycle systems
Supply Chain Model	Semi-linear	Hybrid circular	Fully closed-loop
Policy & Regulation	EPR introduction	Strong enforcement	Global harmonization
Economic Viability	Subsidy-dependent	Profitability emerging	Fully profitable

7. Policy and Industry Collaboration for Circular EV Battery Supply Chains

Public policy is an essential component in promoting the transition towards a circular EV battery ecosystem since it enables the creation of the right economic incentives that promote sustainability. It is through the creation of appropriate regulatory frameworks and enabling conditions that ensure sustainable economic development while promoting environmental goals. For instance, governments play a significant role in encouraging innovation, infrastructure development, and creating economic incentives that encourage sustainable behavior. EPR can be considered as one of the most influential regulatory frameworks in this regard. Through EPR programs, governments make sure that producers take responsibility for managing their products even after they become wastes since it promotes the recovery and recycling of waste products [22]. EPR programs not only promote battery collection but also foster the development of recycling infrastructure since it creates the incentive for investing in such infrastructure. Additionally, public policies also play a critical role in addressing barriers to adoption through the introduction of various financial incentives such as subsidies and viability gap funding. Financial incentives enable companies and countries to invest in recycling infrastructure, especially in developing countries.

7.1Regulatory Standardization and Global Alignment

One significant obstacle to circularity is the issue of non-standardization of battery designs, markings, and recycling methods. There needs to be a move towards standardization through formulation of unified technical standards to ensure compatibility between various stakeholders. Standardization of battery packs design, materials used, and safety practices would lead to reduced costs associated with disassembly and repairs.

On the international front, there is need for harmonization of regulations to enable the flow of end-of-life batteries and recycled materials across national borders. Absence of standard regulations creates many difficulties for businesses trying to adopt circular supply chains. Cooperation is key in developing a regulatory framework that will help advance circularity [23].

7.2Industry Collaboration and Ecosystem Development

A shift toward the circularity of EV battery supply chains cannot be attained through the efforts of each organization acting alone. Such a transformation requires the participation of many stakeholders in the whole value chain, such as automotive OEMs, battery producers, recyclers, energy organizations, and technology providers. Collaboration allows sharing of infrastructures, data, and technologies that can lead to cost reduction and innovations.

For instance, through collaborations with recycling organizations, automotive OEMs ensure material closed-loop and hence facilitate the systematic reintroduction of batteries at the end of their lives back into manufacturing processes. On the other hand, partnerships with energy companies assist organizations in generating second life batteries and hence revenues and extended battery lifespans. Consortium and alliance initiatives are also important in facilitating the achievement of collective goals and the adoption of voluntary standards and best practices.

7.3Digital Collaboration and Data Sharing

The use of digital technologies is key to promoting collaboration in the circular ecosystem. Technologies such as blockchain, IoT, and cloud computing enable secure and transparent data sharing among all participants. An example of this would be the use of blockchain technology to ensure the traceability of batteries from source to destination, thus complying with the environmental policies and ensuring responsible sourcing practices [24].

On the other hand, data sharing through collaborative data platforms enables participants to obtain timely information on the condition, location, and ownership of the batteries. This will enable proper reverse logistics and second life usage. To achieve such integration in the value chain, one must take into consideration issues such as data security and confidentiality.

7.4Public-Private Partnerships (PPPs) & Emerging Economies

PPPs are important in bringing the goals set out in policies and regulations closer to actual industrial practices. There is potential for cooperation between the public sector and private enterprises through joint establishment of recycling plants, centers for research, and pilot tests. Through such partnerships, costs will be reduced for the private sector, and there will be assurance that the goals set out by the government will be met in terms of sustainability. Moreover, PPPs have the potential to encourage skills and workforce training initiatives. These are important for handling recycling processes as well as battery management processes in general.

Collaboration between policy makers and industries is especially important in emerging countries such as India because of the informal sector involved in the process of recycling batteries. The formalization of the informal sector can be achieved through regulatory policies and incentives along with educational programs. Policies by government to encourage the development of local capacity in recycling and dependency on imported materials for recycling are among the main reasons behind the development of the circular economy concept in India [25].

Indian companies including MaxVolt Energy and Maxvolt ReEarth have started working together with the policymakers in order to develop a circular ecosystem according to EPR policy regulations.

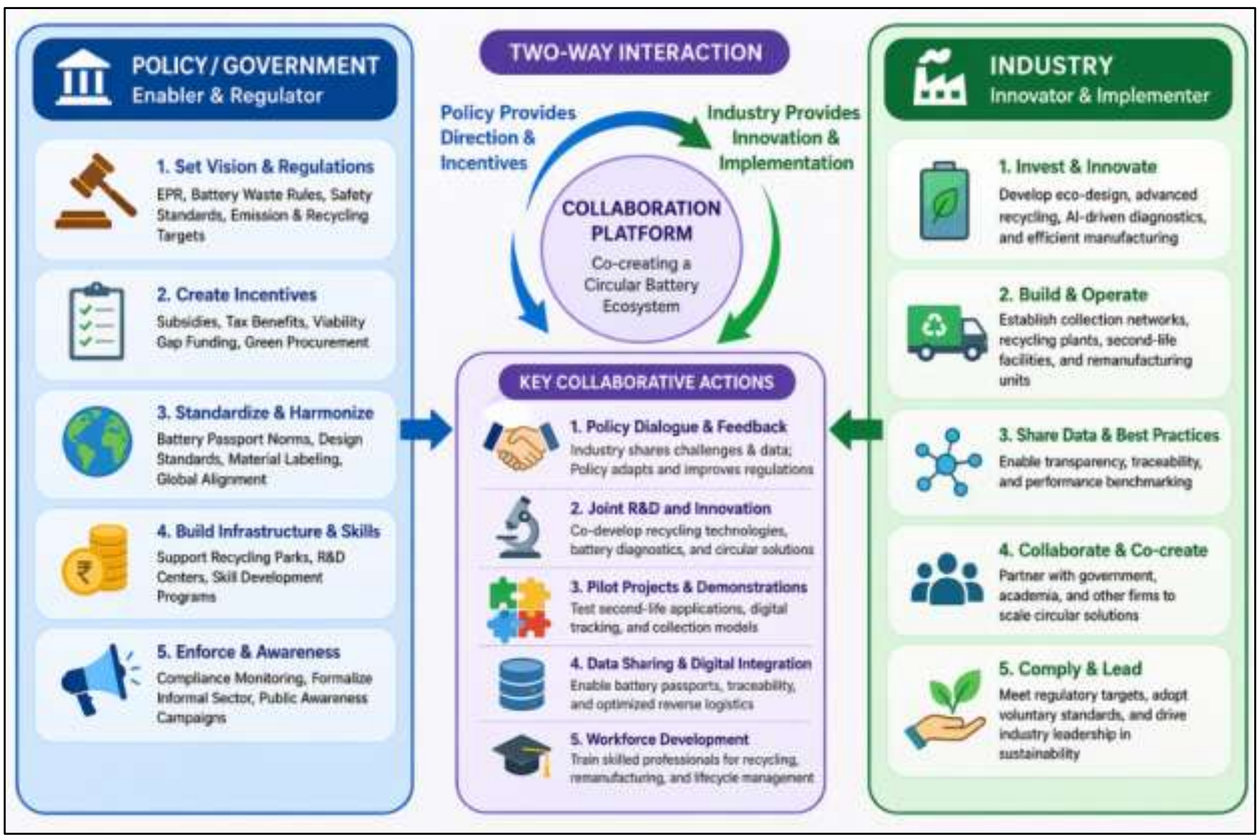

Figure: Policy vs Industry interaction framework

8. CONCLUSION

A shift from a linear to a circular supply chain of EV batteries is not merely recommended but is now a strategic must for sustainable future and resource security. The current research proves that the 6R model (Refuse, Reduce, Reuse, Repair, Remanufacture, Recycle/Recover) can serve as an ideal framework for turning dead batteries into secondary sources of value within an organized timeline (2025-2040) in order to evolve from the stage of developing a battery ecosystem to full-fledged industrial integration and eventually close-loops circularity. The analysis of Maxvolt Energy and Maxvolt ReEarth cases shows that circularity can be performed differently in the ecosystem and other some companies are also advanced in battery recycling,

while others stand out at second-life use or value chain integration. The point is that it takes combined efforts of all stakeholders to develop the ecosystem for achieving true circularity in terms of all six R.
However, there are still some issues regarding technology limitations, economic viability, infrastructure deficiency, and lack of regulation uniformity. Solving these issues would require continuous investments, international standards, and application of modern technologies, such as artificial intelligence, blockchain, and digital twins. New economies, especially in India, can take advantage of their unique position and bypass the linear approach through integrating circular principles directly into EV strategy development. To moving "from waste to resource" is attainable and scalable under the framework of a carefully crafted 6R approach that is complemented by corresponding policies and active involvement of the industry players. A circular EV battery value chain guarantees both environmental benefits and economic advantages in its implementation and operation.

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