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Challenges and Opportunities for Recycling Electric Vehicle Battery Materials

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Abstract:
The urgent need for **cost-effective and energy-efficient solutions** for recycling end-of-life electric vehicle (EV) batteries is driving increased research and policy discussions. This paper draws from existing literature, original research findings, and ongoing Canadian pilot projects to explore key aspects of EV battery recycling:

- **Economic and Environmental Motivations:** The financial incentives and sustainability advantages of recycling.
- **Technical and Financial Barriers:** Challenges in scaling up recycling efforts, including technological limitations and cost concerns.
- **Current Recycling Methods:** Various approaches under consideration for large-scale implementation.

To address these challenges, several **policy and strategic initiatives** are recommended, such as increased funding for both incremental improvements and breakthrough innovations in recycling technology, financial support for pilot projects that promote collaboration across the recycling value chain, and the implementation of market-driven measures to create a favourable economic and regulatory landscape for large-scale EV battery recycling.

Keywords: Electric Vehicle (EV), Recycling, Life Cycle, Sustainability.

Challenges:

Lack of Battery Standardization: EV batteries vary across manufacturers in terms of chemistry, cell design, and packaging, making it challenging to establish universal recycling methods.

Complex Extraction Process: Recycling requires dismantling batteries, separating materials, and recovering valuable metals. Current technologies have low recovery rates, leading to resource wastage.

High Recycling Costs: The process is energy-intensive and expensive, especially with current high-temperature methods.

Regulatory and Policy Challenges: The absence of clear regulations and policies slows down the development of an effective recycling infrastructure.

Lithium-ion batteries (LIBs) dominate electricity storage for high-energy applications like portable electronics and electric vehicles (EVs). The rapid rise of EVs has driven an unprecedented demand for LIBs and the raw materials essential for their production—lithium, cobalt, and nickel. As large-scale mineral extraction, refining, and manufacturing become necessary to support EV mass production, concerns have emerged regarding the long-term sustainability of batteries as a viable solution for decarbonizing transportation.

A key challenge is managing the growing stock of end-of-life (EOL) EV batteries, which must be collected and processed efficiently. By 2030, over 5 million metric tons of lithium-ion batteries (LIBs) are expected to reach EOL, necessitating the development of large-scale recycling infrastructure. Without proper recycling, the valuable—yet often toxic—materials contained in these batteries could be wasted, burdening future generations.

To mitigate these concerns, the battery industry must evolve toward greater social responsibility, environmental sustainability, and economic viability. A circular economy model for battery manufacturing presents a promising solution by reducing both the environmental footprint of batteries and dependence on raw mineral extraction.

Significant advancements are required to achieve **high lithium-ion battery (LIB) recycling rates**, cost competitiveness with virgin materials, and improved energy and environmental footprints compared to non-circular value chains. While various battery recycling solutions already exist, **funding and policy instruments** are essential to establish resilient recycling value chains capable of supporting the anticipated large-scale expansion of electrified transportation.

EV LIB recycling remains in its early stages—particularly outside China—presenting both **challenges and opportunities** for those looking to shape the increasingly strategic landscape of sustainable battery manufacturing.

Economic and Environmental Drivers for Recycling LIBs

1. Mitigating Toxicity, Safety, and Contamination Risks: Lithium-ion batteries (LIBs), particularly EV LIBs, contain **toxic and flammable materials** that pose serious safety hazards. Discarded LIBs in municipal waste systems can easily catch fire or even explode, with waste management facilities frequently experiencing fire incidents caused by consumer LIBs.

Improper disposal—such as landfilling—also threatens **soil and groundwater quality**, introducing toxic and heavy metals like chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), and thallium (Tl) into ecosystems. To prevent environmental degradation and safety hazards, **effective end-of-life (EOL) battery disposal and recycling** are essential for public health and sustainable resource management.

2. Reducing the Carbon Footprint of EVs: Assessing the lifecycle emissions of lithium-ion battery (LIB) manufacturing is complex, but estimates suggest that 30–50% of an EV's greenhouse gas (GHG) emissions stem from battery production and mineral extraction. Despite variations based on country of origin, manufacturer, and battery type, these figures have drawn significant media scrutiny. Differences in methodologies and assumptions for tracking lifecycle emissions further complicate the debate.

Battery production generally has a higher environmental footprint than most internal combustion engine vehicle (ICEV) components. This is largely due to the fact that China, where much of the world's batteries are produced, has a high-carbon electricity grid, exacerbating the emissions impact. One way to lower this footprint is by decarbonizing electricity sources for battery manufacturing plants.

However, another promising solution is battery recycling, which helps reduce reliance on virgin material extraction and refining. Studies by Dunn et al. suggest that EV lifecycle emissions could be reduced by up to 51% through recycling, reinforcing the importance of a circular economy in battery production.

Lowering EV Costs through Battery Recycling

Raw materials contribute to up to 50% of the total cost of a typical lithium-ion battery (LIB). By replacing virgin materials with recycled materials, manufacturers could potentially reduce battery pack costs by up to 30%.

Additionally, recycling eliminates battery disposal fees (or "gate fees") that would otherwise be incurred if spent LIBs were sent to landfills, further improving cost efficiency in the EV industry.

Reducing Reliance on Mineral Extraction

Electric vehicle (EV) manufacturing requires greater mineral resource consumption than internal combustion engine vehicles (ICEVs), largely due to the use of cobalt, nickel, lithium, manganese, and other metals in lithium-ion batteries (LIBs). This dependency has led some researchers to question the long-term sustainability of EVs and whether they truly offer environmental benefits over ICEVs.

Global demand for LIB materials is projected to increase significantly in the next decade—by over 575% for lithium and 1237% for nickel. While the mining industry is expected to scale production to meet this demand, minimizing mineral extraction and processing is preferable due to their substantial environmental impact.

Battery recycling, often termed "urban mining," presents a viable solution to reducing resource consumption. Several lifecycle analysis (LCA) studies suggest that recycling LIBs can significantly mitigate the environmental footprint of EV production. One study estimates that approximately 65% of the cobalt required for vehicle demand in the U.S. could come from recycled LIBs. As the availability of recycled materials increases and EV sales growth stabilizes, recycled components could satisfy a significant portion of material demand.

According to the World Economic Forum (WEF), EVs could become the largest stock of critical battery materials by 2050, highlighting the necessity of an efficient, circular economy model for sustainable battery production.

Battery recycling is set to become a major industry, generating billions in revenue, tax income, and job opportunities, particularly in regions that currently lack battery-related industrial activity. Due to the high transportation costs associated with used battery packs, localizing recycling infrastructure presents a compelling economic incentive.

Governments have strong financial motivations to support EV battery recycling initiatives, ensuring economic benefits stay within their jurisdictions. Canada, particularly Quebec, where EV sales are rising but battery manufacturing is largely absent, has engaged in discussions on attracting investments in this sector.

One proposed strategy is to develop a sustainable end-to-end battery value chain, including:

- **Mineral extraction and refining** (for materials like cobalt, graphite, lithium, and nickel)
- **Battery and EV manufacturing**
- **State-of-the-art end-of-life (EOL) infrastructure**
- **Battery recycling**, all powered by **hydroelectricity and other renewable energy sources**

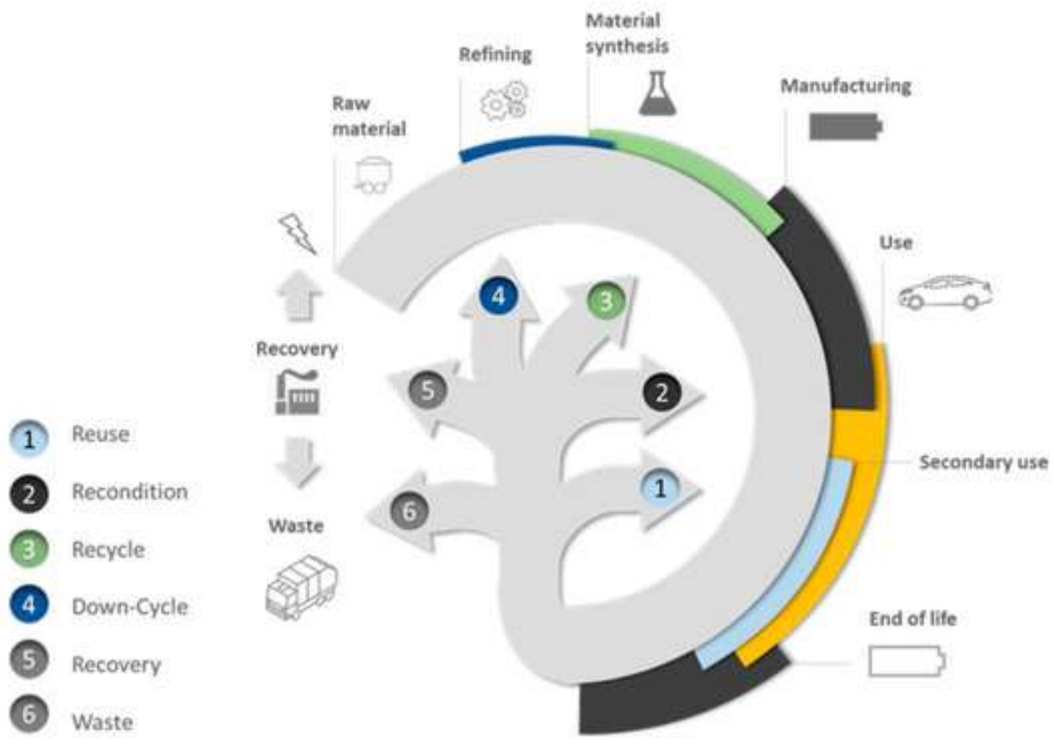
Sharpe et al. emphasize that securing investments in battery production could help Canada maintain a role in the global EV supply chain as its traditional automotive sector faces increasing challenges, including plant closures. Without an EV industry presence, Canada risks losing what remains of its automotive sector. The availability of recycled materials could make battery and EV production more attractive, further supporting local manufacturing growth.

Summary:
Safety and environmental concerns—combined with economic factors and supply chain risk management—are the primary forces driving the growing interest in lithium-ion battery (LIB) recycling. These considerations are also accelerating the shift toward circular business models within the electric vehicle (EV) industry, ensuring a more sustainable and resource-efficient future for battery production and waste management.

Technical and Financial Challenges of LIB Recycling

One strategy to extend the useful life of battery materials is through reuse or reconditioning for second-life applications. At the end of their first lifecycle in EVs, many lithium-ion batteries (LIBs) retain 75–80% of their original capacity, making them viable for less demanding applications.

This process typically involves collecting and reconditioning used EV LIB systems for lower-power applications, such as energy storage and backup power solutions. By extending the lifespan of these batteries, this approach helps reduce lifecycle emissions and lower the demand for critical raw materials, supporting both environmental sustainability and resource efficiency.



Cyclic flowchart of manufacturing, usage, and end of life (EOL) lithium-ion batteries (LIBs).

Challenges in Second-Life Battery Repurposing:

Despite its environmental benefits, second-life battery repurposing faces significant cost barriers, including high refurbishment, transaction, and collection costs. Additionally, uncertainties around quality, safety, and remaining battery lifespan make large-scale implementation difficult.

As the market price of lithium-ion batteries (LIBs) declines and their performance improves, the economic value of used batteries will also decrease, reducing incentives for second-life applications.

While repurposing is a valuable sustainability strategy, it only delays the inevitable need for end-of-life (EOL) solutions, reinforcing the importance of developing efficient recycling infrastructure alongside second-life initiatives.

To achieve a circular economy in EV and battery production, recycling is essential. However, the collection, processing, and repurposing of large batteries pose significant technical and economic challenges. The following obstacles may be particularly difficult to overcome.

1. To ensure high product quality and supplier reliability, battery recycling should ideally restore spent materials to their original high-purity, battery-grade condition for use in EV LIB manufacturing—a process known as **closed-loop recycling**. However, many recyclers opt for **down cycling**, selling recovered materials to industries such as cement production. This occurs either due to technological limitations that prevent refinement to battery-grade materials or strategic decisions to maximize profits by focusing on high-value outputs. While down cycling is preferable to landfill disposal, it does not alleviate supply chain pressures or significantly reduce EV lifecycle emissions. To replace virgin materials, recyclers must consistently provide **reliable, high-quality LIB-grade materials** to battery manufacturers.
2. For battery recycling to be economically viable, the market price of recycled materials must cover collection, transportation, storage, and processing costs while ensuring a reasonable return on investment. Ideally, recycling would compete with raw material extraction, but environmental externalities often keep virgin resource costs artificially low.
3. In reality, recycling is often more expensive due to the numerous steps required to recover and refine materials. For instance, research by Melin suggests that recycling lithium costs **three times more** than mining new lithium, discouraging investment. Additionally, recyclers must navigate a volatile market where prices for virgin materials, such as cobalt and lithium, can drop significantly, making recycling less attractive. Future trends, like the decreasing cobalt content in LIBs, could further challenge the financial feasibility of battery recycling.
4. To minimize environmental impact, battery recycling should reduce the negative effects of landfill disposal and virgin material extraction. However, these processes often require significant electrical and thermal energy and may produce secondary pollutants, including toxic emissions, water contaminants, and solid residues. Additionally, the collection and transportation of used batteries contribute to the overall energy footprint, which must be lower than that of mining and refining raw materials.
5. The key challenge is balancing multiple, sometimes conflicting, goals—ensuring affordability, energy efficiency, environmental responsibility, and safety while delivering materials that meet or exceed the quality, price, and reliability of virgin resources. **Closed-loop recycling** should be prioritized to enhance efficiency and support the long-term sustainability of EVs. Achieving this vision demands substantial investment and technological innovation.

Current Methods for Recycling Lithium-Ion Batteries:

Spent LIBs, whether sourced from end-of-life (EOL) EVs or second-life applications, are typically processed using three main methods: pyro metallurgy, hydrometallurgy, and direct recycling. Hydrometallurgical Recycling of Lithium-Ion Batteries

Hydrometallurgy leverages the high solubility of transition metals and lithium in acid. In this process, spent batteries are crushed, and their components—such as steel, copper foil, and aluminium foil—are sorted using mechanical methods, recovering about 25% of the total value. Electrolyte recovery is possible but remains complex, with limited research conducted in this area.

The primary advantage of hydrometallurgy over pyro metallurgy is its efficient lithium recovery, typically achieved through Li_2CO_3 precipitation following leaching solution purification. Due to this efficiency, hydrometallurgical processes are widely regarded as the most promising method for battery recycling. This is reinforced by scientific literature, with over 75% of research on LIB recycling focusing on hydrometallurgy.

In Canada, several companies—including Retrieve, Lithium Recycling, Neometals, and Li-Cycle—are actively investing in hydrometallurgical recycling facilities to advance sustainable battery recovery.

Direct recycling seeks to restore the original properties and electrochemical capacity of catholic active materials without breaking them down into individual elements. This allows them to be directly reused in the manufacturing of new LIBs. The process involves mechanical, thermal, chemical, and electrochemical methods, ensuring that the recovered material can be reintegrated into battery production.

While recent advancements show promise in improving efficiency, the full restoration of initial cathode capacity remains unproven. Economically, direct recycling can generate high-value products, but it requires complex battery sorting and pre-treatment steps, adding to operational challenges. Another critical issue is that recovered materials may become obsolete by the time they re-enter the market—potentially up to 15 years after the original battery was manufactured—due to the rapid evolution of battery technology.

Pyro metallurgy involves smelting batteries at high temperatures (~1500 °C), effectively burning all carbon-based compounds. This process consolidates valuable metals such as cobalt, nickel, and manganese into an alloy, which can then undergo hydrometallurgical treatment to extract individual elements. A key advantage is that it minimizes handling by eliminating crushing and other pre-treatment steps. However, electrolyte, graphite, steel, aluminium, and lithium are lost as slags or off-gas during processing.

A significant drawback of pyro metallurgy is the high cost of gas effluent treatment facilities needed to prevent the release of toxic emissions. Additionally, it fails to extract value from lower-cost LIB chemistries such as LiFePO4, LiMnO2, and LiTiO4, as these materials end up in waste by-products.

In summary, while multiple battery recycling solutions are available, substantial innovation is still required to enhance recycling efficiency, achieve cost competitiveness with virgin materials and battery suppliers, and minimize energy consumption and environmental impact—surpassing the limitations of non-circular value chains.

Policy Implications:

Large-scale lithium-ion battery (LIB) recycling remains in its early stages, particularly outside China. Currently, most LIBs end up in landfills after only a few years of use. Even in the European Union, where battery recycling regulations are relatively advanced, only 20% of spent LIBs were collected in 2016.

A major factor behind this low recycling rate is the dominance of small consumer electronic batteries, which are difficult to recycle due to their size and low economic value. However, recycling EV batteries also presents substantial challenges, as outlined previously.

To establish robust recycling value chains, policy support is essential. Funding and regulatory measures must help recycling compete with virgin material supply chains in terms of cost, quality, and reliability.

Additionally, recycling should provide superior safety, environmental benefits, and energy efficiency compared to traditional, non-circular approaches to end-of-life (EOL) battery management.

Policymakers seeking to accelerate investment in this sector should focus on three key priorities: **(i) funding for Research and Development (R&D)** to drive technological advancements, **(ii) support for pilot projects** to validate and scale innovative recycling solutions, and **(iii) market-pull measures** to create a favorable investment environment for LIB collection and recycling.

R&D Priorities:

Advancing battery recycling technology is a recognized global priority, with research output increasing significantly—particularly in China. The World Economic Forum (WEF) has emphasized the need for technological and process improvements to enhance recovery rates and environmental performance.

Several notable R&D initiatives are driving innovation in this field:

Relieve Project – A collaboration between Era met Lithion Recycling claims to achieve 95% recovery of spent LIB materials into battery-grade outputs, covering various chemistries, including Lithium Cobalt Oxide (LCO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Manganese Oxide (LMO), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Iron Phosphate (LFP), while also reclaiming spent electrolytes.

A promising approach developed by Hydro-Quebec focuses on selective lithium extraction for recycling LFP-based batteries. Traditional lixiviation techniques dissolve the black mass entirely, recovering elements like cobalt, nickel, and manganese but losing $LiFePO_4$ nanoparticles, yielding only low-value iron and phosphate compounds. In contrast, Hydro-Quebec's process preserves $FePO_4$ nanoparticles by selectively extracting lithium ions and relithiating the material, restoring LFP nanoparticles to their original pristine state with full electrochemical activity.

This patented method replaces highly corrosive acids (e.g., H_2SO_4 or HCl) with CO_2 gas, which solubilizes lithium as $LiHCO_3$ while leaving $FePO_4$ intact. After filtration, $LiHCO_3$ is converted into Li_2CO_3, which can be used to produce new lithium batteries, while CO_2 is recycled back into the process, ensuring minimal environmental impact.

The development of innovative recycling approaches can address critical limitations in conventional processes, enabling the recovery of key battery materials like LFP while reducing reliance on hazardous chemicals that cannot be regenerated.

- To enable efficient disassembly, recycling, and repurposing for second-life applications, batteries should be designed with recyclability in mind. Unlike lead-acid batteries, which are widely recycled, lithium-ion batteries (LIBs) contain a diverse range of materials—including transition metals, graphite, aluminum, plastics, steel, and electrolyte solutions—making the recycling process more complex.
- Battery packs also include sensors, circuitry, and electronic components, adding another layer of difficulty for recyclers. Additionally, the automotive industry employs various LIB chemistries—such as LFP, LCO, NCA, LMO, and NMC—each with its own unique material composition. Recyclers must also navigate differences in battery size and format, including cylindrical, prismatic, and pouch-type cells, further complicating recovery efforts.
- Would you like insights into battery design strategies that could improve recyclability?
- Standardizing battery technologies remains highly complex, as variations in design and material composition are essential for meeting the specific energy and power demands of different EV models. Even within a single automaker, multiple battery chemistries and geometries may coexist, providing

opportunities for competitive advantage and intellectual property protections in the battery and EV industry.

- Despite these complexities, design-for-recyclability approaches are gaining traction. This includes making battery packs and modules easier to remove, disassemble, and repurpose, as well as selecting materials that can be safely and efficiently recycled. While recyclability could become a competitive advantage for manufacturers, it is currently overshadowed by concerns such as price competition, energy density, safety, longevity, and cycle life. However, as regulatory pressures increase and recycling becomes more economically viable, the need for recyclability-focused designs will grow.
- Another critical factor is understanding battery degradation over time. Gaining deeper insights into cell aging mechanisms, including structural changes, electrolyte evaporation, decomposition, and collector corrosion, will improve recycling strategies—particularly for direct recycling processes. Optimizing these aspects will play a vital role in advancing sustainable battery recovery and repurposing efforts.
- Would you like to explore specific design innovations that could improve battery recyclability?
- Suez, BASF, Chime Aristech, and the Norwegian University of Science and Technology, focused on improving Li-ion battery recycling for electric vehicles.
- Recall Centre (Argonne National Laboratory) – Developing a novel direct recycling process aimed at optimizing material recovery for battery reuse.
- Canadian Research Initiatives – Led by organizations such as Hydro-Quebec Centre of Excellence, the University of Montreal, the National Center in Environmental Technology and Electrochemistry (CNETE), and the National Research Council of Canada (NRC), these projects are advancing sustainable battery recycling solutions.
- While providing detailed recommendations for future R&D efforts is beyond the scope of this paper, a few key considerations can be highlighted.
- First, the entire recycling value chain must be addressed. Battery recycling logistics—including collection, transportation, sorting, and storage of end-of-life (EOL) batteries—have been largely overlooked in scientific literature, despite their significant impact on costs, safety, and efficiency. Advanced automation and artificial intelligence (AI) technologies could enhance these processes, improving operational effectiveness. Notably, safely transporting spent batteries accounts for 40–50% of overall recycling costs, while vehicle dismantling and battery pack disassembly remain expensive due to safety risks associated with manual handling.
- Second, R&D efforts should prioritize closed-loop recycling for all LIB types and battery components. The shift toward hydrometallurgical processes has been driven by the need to improve recycling rates and recover neglected materials such as electrolyte solutions, aluminium, graphite, and lithium. Further advancements are required to ensure higher recycling rates across various battery chemistries while maintaining cost efficiency and performance standards.
- Identifying gaps in existing knowledge and setting R&D priorities for battery recycling is an ongoing effort. While research on specific recycling processes is critical, a holistic approach that considers the entire battery value chain—from design and manufacturing to end-of-life (EOL) collection and recycling—is necessary for meaningful progress.
- One initiative working toward this goal is a community of interest on battery recycling, established in Quebec with the support of InnovÉÉ. By fostering dialogue, goal-setting, and collaborative R&D projects among stakeholders across the battery and recycling ecosystem—such as OEMs, battery

manufacturers, transportation companies, and recyclers—this initiative aims to bridge the gap between scientific research and market demands.

- Expanding public research budgets will be essential to advancing scientific and engineering expertise in LIB recycling. However, investment levels remain relatively low compared to the scale of challenges facing battery sustainability. Gaines et al. have recommended that U.S. federal funding for LIB recycling be on par with battery R&D funding, a principle that could be applied to other jurisdictions as well.

Pilot Projects:

- While expanding R&D in recycling value chains and battery recyclability is highly beneficial, there are already several existing solutions for EV battery recycling. Therefore, policy priorities should also focus on supporting pilot projects that assess the technical and financial viability of these solutions.
- Pilot projects play a crucial role in developing integrated recycling and LIB manufacturing value chains, providing valuable investment planning data, and identifying knowledge gaps for further research. These initiatives should engage stakeholders across the battery ecosystem—including automotive, battery, transportation, and recycling industries, as well as regulators and scientific researchers.
- One major hurdle for recyclers is ensuring a stable supply of spent batteries. Industry sources indicate that current recycling capacity is underutilized, suggesting the need for better EOL battery consolidation. Improved cooperation and communication along the value chain could help overcome these challenges. Furthermore, pilot programs would allow battery manufacturers to evaluate the quality and usability of recycled materials while gaining familiarity with closed-loop recycling approaches.
- EV fleets present a strong opportunity for pilot projects. Fleet operators—including transit and school buses, taxis, delivery vans, car-sharing, and rental services—are highly focused on asset productivity and total cost of operation (TCO). This gives them a natural incentive to reduce disposal fees and maximize resale value for used components. Additionally, fleets provide a consistent and consolidated supply of spent batteries, lowering transaction and transportation costs while offering more uniform battery types, simplifying recycling.
- Another key priority for pilot projects is to evaluate energy consumption and lifecycle emissions of recycling methods. Currently, industrial recycling data remains limited, particularly concerning solvent use in hydrometallurgical processes and energy requirements in pyro metallurgical methods.

Market Creation for Battery Recycling:

To successfully scale up and optimize recycling value chains, technology-driven initiatives must be complemented by market-pull policies that incentivize investment, especially during the industry's early stages. As Gaines et al. noted, effective policy mechanisms and incentives are needed to encourage battery collection, process improvements, infrastructure development, and cost reduction in recycling. Without such measures, recycling faces a chicken-and-egg problem, where the low availability of end-of-life (EOL) batteries discourages companies from investing in recycling infrastructure, further delaying the development of battery collection, transportation, and recycling-related R&D.

A key regulatory approach under consideration is Extended Producer Responsibility (EPR), which would require EV manufacturers to cover battery collection and recycling costs. This policy would encourage automakers to establish efficient recycling networks and integrate design-for-recycling principles into battery production. China has already adopted strict lifecycle regulations, holding car manufacturers and importers responsible for battery collection, repurposing, and recycling.

Several **market-pull strategies** could further accelerate battery recycling efforts:

- Setting cost and performance benchmarks with rewards or penalties—such as the U.S. Department of Energy's $5.5 million prize for a profitable process capturing 90% of spent LIBs.
- Raising gate fees and increasing landfill costs for EOL LIBs.
- Implementing a deposit scheme at the time of EV purchase, refundable upon battery collection.
- Taxing virgin materials to improve price competitiveness of recycled materials, ideally based on embedded GHG emissions.
- Standardizing battery labelling to facilitate sorting and recycling. The World Economic Forum (WEF) recommends a "battery passport", tracking chemistry, origin, and state of health throughout its lifecycle. China already mandates such tracking, and the Global Battery Alliance suggests expanding it to include compliance with human rights laws and sustainability goals.
- Supporting regional integration through international agreements to reduce transportation costs while maintaining safety.

While these policies promise environmental and economic benefits, they also carry risks. Some measures may increase costs, potentially affecting EV demand. Policymakers must carefully balance sustainability goals with the affordability of EVs, given that EVs already reduce lifecycle GHG emissions despite battery production impacts. Rather than imposing strict regulatory constraints, a gradual approach—coupling market footholds for EV adoption with expanded tax policies and recycling incentives—could prove more effective in the long run.

Governments, including those of Canada and Quebec, should take these considerations into account as they strive to establish leadership in battery manufacturing and clean transportation.

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