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Sustainable Development and Green Job Creation in Canada's EV Battery Recycling Sector

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Abstract

The rapid growth of electric vehicles in Canada is expected to generate significant volumes of end-of-life lithium-ion batteries, creating both environmental challenges and opportunities for circular resource management. This study develops an integrated Agent-Based Modeling framework to analyze the lithium-ion batteries lifecycle, including remanufacturing, second-life applications, and recycling within Canada's electric vehicle ecosystem. Using electric vehicle and plug-in hybrid electric vehicle registration data from Statistics Canada (2017-2025), the model estimates future end-of-life battery generation and material flows. A state of health based cascading approach is applied, where batteries are directed to remanufacturing, second-life use, or recycling based on their remaining capacity. Recycling enables recovery of critical materials such as lithium, nickel, and cobalt, reducing reliance on virgin resource extraction. Environmental and socio-economic impacts are quantified through greenhouse gas emission reductions and green job creation. Results show that LIB recycling can significantly reduce greenhouse gas emissions while generating substantial employment opportunities. Policy scenario analysis, including baseline, Extended Producer Responsibility, and incentive-based systems, demonstrates that stronger policy interventions improve collection efficiency, recycling rates, and overall system performance, supporting circular economy development in Canada's electric vehicle sector.

Keywords
Electric vehicles, Sustainable development goals, Recycling, Lithium-ion batteries, Agent-based modeling, Circular economy

1. Introduction
The global transition toward electric mobility has significantly increased demand for lithium-ion batteries (LIBs), making them central to decarbonized transportation systems. In Canada, rising electric vehicle (EV) adoption is expected to generate a substantial volume of end-of-life (EOL) batteries in the coming decades (Slattery et al., 2024). While this supports climate goals, it also introduces challenges related to resource security, material recovery, and waste management. EV batteries typically reach EOL for vehicle use at around 80% capacity, with lifespans of 8-12 years, followed by up to 10 years in second-life applications (Akram and Abdul-Kader, 2021).

Canada's LIB recycling industry remains in an early stage but shows strong growth potential. Companies such as Retriev Technologies and Glencore Canada Corporation are actively engaged in hydrometallurgical recycling (Beaudet et al., 2020). Strengthening recycling infrastructure is critical to enabling a circular economy and reducing environmental impacts. LIBs depend on critical materials such as lithium, nickel, and cobalt, whose limited geographic distribution creates supply chain risks and environmental concerns due to energy intensive extraction processes (EuRIC AISBL, 2020). Recycling and reuse offer viable pathways to reduce dependence on virgin materials and lower greenhouse gas (GHG) emissions. EOL batteries can be reintegrated through remanufacturing, second-life applications, and material recovery. However, optimizing these pathways requires a system level understanding of interactions among stakeholders, including EV owners, collection networks, repurposing systems, and recycling facilities (Yu et al., 2022).

Existing studies primarily emphasize technical and environmental aspects of lithium-ion battery systems, with limited integration of system dynamics, policy mechanisms, and socio economic impacts. In particular, there is a lack of holistic modeling approaches that capture interactions across the full battery lifecycle, including remanufacturing, second-life applications, collection logistics, and recycling processes under different policy environments.

To address this gap, this study develops an Agent-Based Modeling (ABM) framework to analyze the LIB lifecycle within Canada's EV ecosystem. The model captures interactions among key agents, including EV owners, remanufacturing units, second-life operators, collection centers, and recycling facilities under baseline, Extended Producer Responsibility (EPR), and incentive-based policy scenarios. It evaluates system performance in terms of battery flows, material recovery, greenhouse gas emission reductions, and employment generation. The framework adopts a cascading circular structure in which batteries transition through remanufacturing, second-life use, and final recycling, ensuring maximum resource utilization across the lifecycle. Overall, this study contributes a system level modeling approach that estimates EOL battery flows, quantifies environmental and socio economic benefits, and supports evidence based policy development for a sustainable circular battery economy in Canada. Figure 1 illustrates the lifecycle of LIB used in EV.

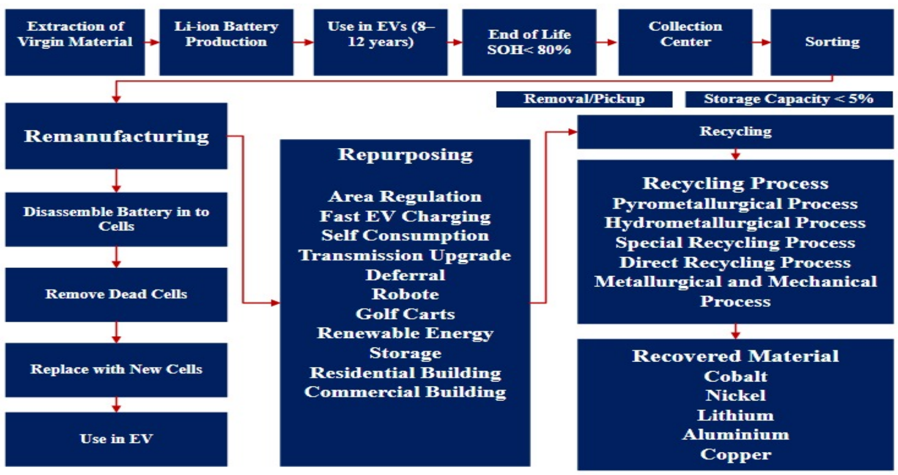

Figure 1. Life Cycle of EV Battery

The remainder of this paper is structured as follows: Section 2 presents the literature review, Section 3 describes the methodology and model formulation, Section 4 discusses the results and policy implications, and Section 5 concludes the study with key findings and recommendations.

2. Literature Review

The rapid growth of EV has significantly increased demand for LIBs, intensifying pressure on critical raw material supply chains. Key materials such as lithium, nickel, and cobalt are geographically concentrated, with over 50% of cobalt sourced from the Democratic Republic of Congo and around 80% of lithium from Australia and Chile (Zeng et al., 2022). This concentration creates supply risks, including geopolitical uncertainty and price volatility (Chen et al., 2019). LIB recycling has therefore emerged as a strategic pathway to enhance material security, reduce dependence on primary extraction, and support sustainable energy transitions. Recycling EOL LIBs from EVs and other applications provides a secondary supply of critical materials, contributing to circular economy objectives and resource diversification (Yu et al., 2022). It also reduces environmental burdens associated with energy intensive mining and refining, with significant potential for GHG emissions reduction through recovery of lithium, cobalt, nickel, and aluminum (Euric Aisbl, 2020).

A substantial body of literature has examined LIB recycling from technological, environmental, and policy perspectives. Rehman et al. (2025) and Zhao and Kaur (2025) review recycling workflows, technologies, and policy developments, while Slattery et al. (2024) explore evolving EOL pathways in North America. Biswal et al. (2024) highlight technological advancements and environmental performance, whereas Akram and Abdul-Kader (2023; 2020) examine circular economy integration and industrial recycling efficiencies. Beaudt et al. (2020) identify key barriers including economic feasibility and supply chain constraints, and Malhi (2020) discusses reuse and second-life battery systems in the Canadian context. Canada is emerging as a key player in the LIB recycling value chain, supported by EV growth and net-zero commitments. Industrial actors such as Li-Cycle, operating large scale hydrometallurgical facilities, and Lithion Technologies, developing innovative recovery processes, are central to this ecosystem. These firms strengthen domestic recycling capacity and align with Canada's critical mineral strategy and circular economy objectives. From a methodological perspective, LIB recycling systems have been studied using life cycle assessment (LCA), material flow analysis (MFA), system dynamics, and optimization models. However, these approaches often assume static structures and limited behavioral representation. ABM has therefore emerged as a complementary tool for capturing heterogeneous actors and decentralized decision making in recycling systems, particularly under policy interventions such as EPR and incentive schemes (Zhang et al., 2021; Liu et al., 2022).

Recycling technologies for LIBs include mechanical, pyrometallurgical, hydrometallurgical, direct recycling, and hybrid approaches. These differ in recovery efficiency, energy demand, emissions, and suitability for different chemistries. Hydrometallurgical processes generally offer higher selectivity for critical metals, while direct recycling provides potential advantages in energy efficiency. Trade offs among these methods remain central to optimizing sustainable recycling pathways. The comparative characteristics of these processes are summarized in Table 1. (Akram and Abdul-Kader, 2023).

Table 1. Comparison of Lithium-Ion Battery Recycling Processes

Process Type	Process Description	Recovery Efficiency	Energy Use	Emissions	Cost	Key Advantages	Key Limitations
Mechanical Processing	Physical dismantling, shredding, and separation into fractions such as aluminum, copper, ferrous metals, and black mass	Low (pre-processing stage only; does not recover pure metals)	Low	Low	Low	Essential preprocessing step; simple and scalable	Does not recover high-purity materials; safety risks from residual charge
Pyro-metallurgical Recycling	High-temperature smelting to produce metal alloys and slag	Moderate for Ni, Co, Cu; Low for Li (lost in slag)	High	High	High (capital + energy intensive)	Robust; can manage mixed and contaminated feedstock	High energy consumption; low lithium recovery; higher environmental impact
Hydro-metallurgical Recycling	Chemical leaching followed by purification (solvent extraction, precipitation)	High for Li, Co, Ni	Moderate to Low	Low to Moderate	Moderate	High recovery efficiency; lower temperature operation; suitable for critical metals	Requires chemical inputs; generates wastewater; process complexity
Direct Recycling	Recovery and reconditioning of cathode materials without breaking into elements	High (material recovery)	Low	Low	Low to Moderate	Preserves cathode structure; lowest environmental footprint	Limited to specific chemistries; requires sorted and high-quality feedstock;

							scalability challenges
Metallurgical and Mechanical Recycling	Combination of mechanical grinding and chemical reactions to enhance leaching and recovery	Moderate to High (emerging)	Low to Moderate	Low	Moderate	Improved leaching efficiency; potential use of waste reagents; environmentally promising	Still at research/pilot stage; limited industrial scalability

Despite progress, gaps remain. Existing studies often rely on deterministic frameworks with limited treatment of uncertainty in technology evolution, policy impacts, and battery demand. Moreover, there is limited integration of ABM with industrial ecology based material flow modeling at the national scale. Few studies also provide Canada-specific dynamic modeling of EV adoption, recycling capacity, and policy mechanisms in a unified framework. This study addresses these gaps through an integrated ABM material flow approach to evaluate LIB recycling under multiple policy and technological scenarios.

2.1 Primary Contributions

- To develop an Agent-Based Model to analyze the full lifecycle of LIB in Canada's EV ecosystem.
- To introduction of a state-of-health (SOH) driven transition framework to model battery flow from EV use to second-life applications and final recycling.
- To estimate EOL battery generation and total mass using real EV and PHEV registration data (2017-2025) within a full lifecycle structure.
- To assess the critical material recovery potential (Li, Ni, Co) for supporting secondary supply chain development and enhancing resource sustainability.
- To quantify the environmental (GHG reduction) and socio-economic impacts, including green job creation across the battery recycling value chain.
- To evaluate policy scenarios (baseline, EPR, and incentive-based) and develop a decision support framework aligned with SDG 8 and SDG 13.

3. Methodology

This study develops an ABM framework to analyze the lifecycle of LIB within Canada's EV ecosystem. The model analyzes the movement of individual battery agents through multiple lifecycle stages, including EV use, remanufacturing, second-life applications, collection, and recycling.

3.1 Model Agents and Behavior

The proposed ABM analyzes LIB lifecycles within Canada's EV ecosystem using five agent types: EV owners, remanufacturing facilities, repurposing facilities, collection centers, and recyclers. Each battery agent is defined by attributes such as registration year, capacity, SOH, and lifecycle stage. The model runs in annual time steps and tracks battery transitions across stages using predefined SOH thresholds. Batteries enter through EV and PHEV adoption and degrade over time due to cycling, usage, and calendar aging. Based on SOH, they transition through remanufacturing, second-life applications, and eventually recycling. These interactions generate system wide flows, with aggregate outcomes including EOL battery generation, material recovery, GHG emission reductions, and employment under different policy scenarios. A unified SOH framework ensures consistent classification across all stages (Akram and Abdul-Kader, 2024).

- Remanufacturing: SOH > 80%
- Second-life applications: 40% ≤ SOH ≤ 80%
- Less demanding applications: 10% ≤ SOH < 40%
- Recycling: SOH < 10%

3.1.1 EV Owner Agent

EV owner agents represent users whose batteries degrade over time due to operational use and aging. Battery state transitions are governed by SOH as follows:

$$EV_i(t) = \begin{cases} \text{Active Use / Remanufacturing}, & SOH_i(t) > 0.80 \\ \text{Second-Life Applications}, & 0.40 \le SOH_i(t) \le 0.80 \\ \text{Less Demanding Applications}, & 0.1 \le SOH_i(t) < 0.40 \\ \text{End-of-Life Recycling}, & SOH_i(t) < 0.1 \end{cases}$$

where $SOH_i(t)$denotes the state of health of battery $i$at time t.

3.1.2 Remanufacturing Agent

Remanufacturing agents restore batteries with sufficient remaining capacity for continued EV use. Eligibility is defined as:

$$Remanufacturing_i = \begin{cases} 1, & Capacity_i > 0.8C_0 \\ 0, & \text{otherwise} \end{cases}$$

where C_0 is the original battery capacity.

3.1.3 Repurposing (Second Life) Agent

Batteries with moderate degradation are assigned to second-life applications such as stationary storage and grid support:

$$Repurpose_i = \begin{cases} 1, & 0.4C_0 \le Capacity_i \le 0.8C_0 \\ 0, & \text{otherwise} \end{cases}$$

Batteries with further reduced capacity are still utilized in less demanding applications:

$$LightUse_i = \begin{cases} 1, & 0.1 \le Capacity_i < 0.4C_0 \\ 0, & \text{otherwise} \end{cases}$$

This cascading structure maximizes battery utilization prior to recycling.

3.1.4 Collection Center Agent

Collection center agents aggregate batteries exiting second-life and less demanding applications. The number of batteries collected at center $j$is given by:

$$B_j = \sum_{i=1}^{n} (Repurpos\,e_i + LightUse_i)$$

Collection centers perform three key functions: (i) collection and transportation, (ii) SOH based sorting, and (iii) safety testing for recycling eligibility. Batteries passing safety requirements are forwarded to recycling facilities.

3.1.5 Recycling Facility Agent

Recycling facility agents process batteries that have reached EOL:

$$REC_i = \begin{cases} 1, & SOH_i < 0.1 \\ 0, & \text{otherwise} \end{cases}$$

These facilities recover critical materials including lithium (Li), nickel (Ni), and cobalt (Co), reducing dependence on virgin extraction and associated environmental impacts.

3.1.6 System Flow Summary

The complete battery lifecycle follows a cascading circular economy pathway:

EV Use → Remanufacturing (SOH > 80%) → Second-Life Applications (40% ≤ SOH ≤ 80%) → Less Demanding Applications (10% ≤ SOH < 40%) → Recycling (SOH < 10%)

This structure ensures maximum value extraction prior to final material recovery. Figure 2 illustrates the ABM structure and agent interactions within Canada's EV battery ecosystem.

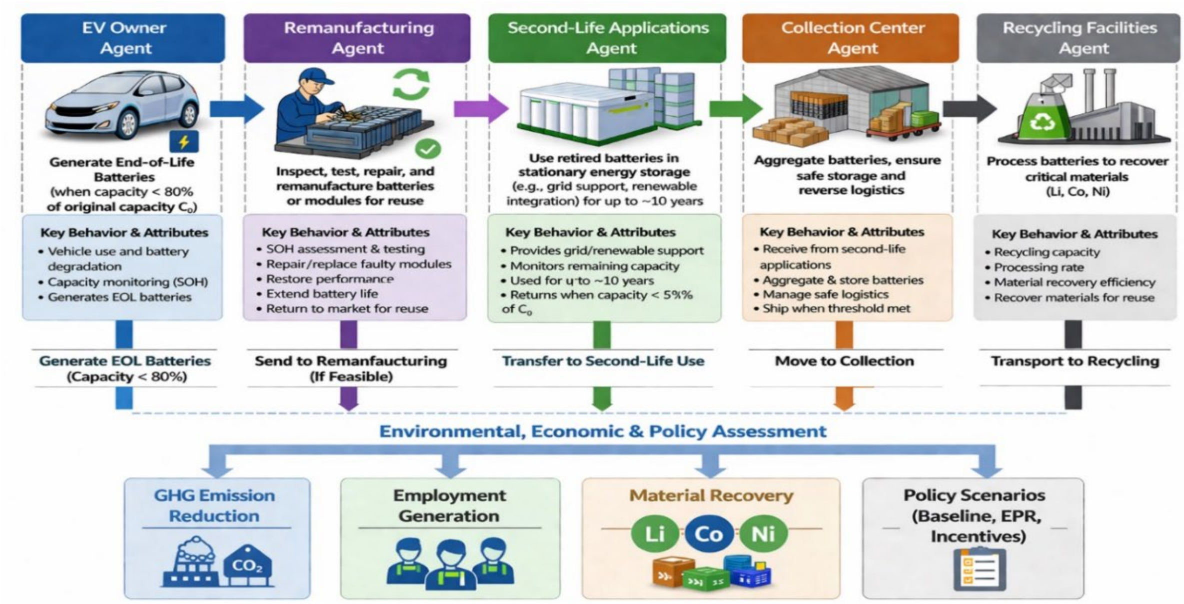

Figure 2. Agent-Based Model for EV Battery Lifecycle

3.2 Model Dynamics
The model operates on annual time steps using EV and PHEV registration data from 2017-2025. In each period, battery agents age and transition across lifecycle states according to SOH based decision rules defined in Section 3.1. Agent interactions determine system flows through remanufacturing, repurposing, collection, and recycling pathways, while system level outcomes emerge from aggregated transitions. Due to limited availability of historical LIB recycling data in Canada, the current model implementation adopts deterministic transition rules with scenario based parameterization. To assess robustness, a sensitivity analysis is conducted by varying collection efficiency ($\beta = 0.85\text{-}0.95$) and battery capacity (40-100 kWh). Results indicate stable and monotonic system behavior across all key performance indicators, including material recovery, GHG reduction, and employment generation. Future extensions will incorporate stochastic agent behavior, Monte Carlo simulation, uncertainty quantification, and empirical validation as additional data become available.

3.3 Model Equations and Variable Definitions
The integrated model combines battery lifecycle dynamics, material recovery, environmental impact, and employment generation within a unified analytical framework. The equations are structured sequentially to represent the flow of LIB from EOL generation through second-life utilization to final recycling outcomes.

i. Battery Flow Dynamics

End-of-Life Battery Generation:

$$EOL_t = \sum_{i=1}^{t} R_i \times f(t-i) \qquad (1)$$

Where R_i represents EV and PHEV registrations, and $f(t-i)$ is the retirement function. A fixed battery lifecycle of 12 years in EV use followed by up to 10 years in second-life applications is assumed, resulting in an approximate 22-year time lag.

Batteries Available for Recycling:

$$RB_t = (1-\lambda)(EOL_t - SL_t) \qquad (2)$$

Where RB_t is the number of batteries available for recycling, SL_t is the number diverted to second-life applications, and λ is the battery loss rate representing batteries not recovered due to degradation, damage, or informal disposal.

Recycled Batteries:

$$REC_t = \beta \times RB_t \qquad (3)$$

Where REC_t is the number of batteries successfully collected and recycled, and β is the collection efficiency under each policy scenario. The loss rate (λ) and collection rate (β) jointly determine recycling outcomes. The loss rate reduces the available battery stock in Equation (2), while the collection rate determines the proportion recovered through Equation (3). Consequently, lower λ and higher β increase recycled battery volumes, material recovery, GHG emission reductions, and employment generation.

ii. Material Recovery

Recovered Materials:

$$Material_{m,t} = \frac{N_t \; X \; C_{avg} \; X \; R_m}{1000} \qquad (4)$$

$Material_{m,t}$ represents recovered material (tons), where N_t is the number of batteries processed for recycling ($N_t = REC_t$), C_{avg} is the average battery capacity (60 kWh), and R_m is the material recovery rate (kg/kWh). The 60-kWh assumption reflects the dominant mid-range EV battery segment in Canada (IEA, 2023) and ensures consistency in estimating material flows and comparing policy scenarios.

iii. Environmental Benefits

Total Recycled Battery Weight:

$$W_{recycle,t} = REC_t \; X \; w_{avg} \qquad (5)$$

where $W_{recycle,t}$ is the total recycled battery weight (tons) and w_{avg} is the average battery weight (tons per unit).

GHG Emission Reduction:

$$GHG_t = W_{recycle,t} \; X \; E \qquad (6)$$

where GHG_t is total avoided emissions (tons CO_2) and E is the emission reduction factor (tons CO_2 per ton recycled). This quantifies environmental benefits by reducing reliance on energy-intensive virgin material extraction.

iv. Employment Generation

Jobs Created:

$$Jobs_t = \frac{W_{recycle,t}}{1000} X \; J \qquad (7)$$

where $Jobs_t$ is total employment and J is the jobs generated per 1,000 tons of recycled batteries. This reflects the labor intensity of recycling, particularly in collection, sorting, and dismantling.

3.3.1 Model Parameters

Table 2 summarizes the full set of model parameters used in the analysis.

Table 2. Model Parameters

Parameter	Description	Value	Unit	Source/Assumption
C_{avg}	Average battery capacity	60	kWh	Calculated (IEA, 2023)
R_{Li}	Lithium recovery rate	0.073	kg/kWh	(Akram and Abdul-Kader, 2021)
R_{Co}	Cobalt recovery rate	0.116	kg/kWh	(Akram and Abdul-Kader, 2021)
R_{Ni}	Nickel recovery rate	0.4	kg/kWh	(Akram and Abdul-Kader, 2021)
β(Baseline)	Collection rate	0.85	–	Scenario
β(EPR)	Collection rate	0.90	–	Scenario
β(Incentive)	Collection rate	0.95	–	Scenario
E	Emission reduction factor	3.6	tCO_2/ton LIB	(Goyal, 2025).
J	Employment factor	15	jobs/1000 tons	(Drabik and Rizos 2018; Akram and Abdul-Kader, 2020).
w_{avg}	Average battery weight	0.416	tons	Calculated (ACE, 2024)

Parameter	Description	Value	Unit	Source/Assumption
λ	Loss rate	0.05	–	Assumed

4.0 Results and Discussions

This section presents the projected volumes of EOL EV batteries in Canada and discusses the associated environmental benefits and employment opportunities from LIB recycling.

4.1 Retired EV Batteries

Battery mass was estimated using a pack level specific energy of 0.15 kWh/kg (150 Wh/kg), consistent with EV battery life cycle assessment assumptions (Ellingsen et al., 2014). This study considers a battery capacity of 60 kWh, representing a typical mid range EV configuration. Following Akram and Abdul-Kader (2021), LIBs are assumed to have a 22-year lifecycle (12 years in EV use and 10 years in second-life applications). Using Statistics Canada (2025) EV and PHEV registration data, the annual number of EOL batteries and their total weight were estimated and are presented in Table 3.

Table 3. Number of LIBs Available for Recycling and Total Weight

Year	Number of New EV and PHEV Registrations	Annual Number of LIBs Available for Recycling (Year)	Total Number Of LIB Available for Recycling After 5% Reduction	Total Weight of LIBs (Tons)
2017	19,696	2039	18,712	7,784
2018	44,283	2040	42,069	17,500
2019	56,165	2041	53,357	22,197
2020	54,353	2042	51,636	21,481
2021	86,267	2043	81,954	34, 093
2022	123,610	2044	117,430	48,851
2023	188,750	2045	179,312	74,594
2024	270,985	2046	257,436	107,093
2025	177,034	2047	168,182	69,964

4.2 Environmental Benefits

Battery recycling reduces energy use and GHG emissions by lowering demand for virgin materials and associated transportation. About 50% of LIB manufacturing emissions come from raw material extraction (ICCT, 2018), which can be mitigated through recycling. Studies estimate that recycling 1 kg of LIB reduces emissions by 2.7-4.6 kg CO_2 equivalent, with an average of 3.6 kg CO_2 equivalent used in this study (Goyal, 2025). The resulting savings are presented in Table 4.

Table 4. GHG Emission Saving

year	End of Life LIB Weight (Tons)	GHG Emission Saving (Tons)
2039	7,784	28,022
2040	17,500	63,000
2041	22,197	79,909
2042	21,481	77,332
2043	34, 093	122,735
2044	48,851	175,864
2045	74,594	268,538
2046	107,093	385,535
2047	69,964	251,870

4.3 Employment Benefits

Using Statistics Canada (2025) EV and PHEV registration data, job creation from end-of-life LIB recycling is estimated after both EV and second-life use. Processing 1,000 tons of LIB generates 15 jobs, 12 in collection and dismantling and 3 in recycling (Drabik and Rizos, 2018; Akram and Abdul-Kader, 2020). By employing the information presented in Table 3, the total job opportunities are calculated and presented in Table 5.

Table 5. Projected Employment from LIB Recycling

year	End of Life LIB Weight (Tons)	Employment Opportunities
2039	7,784	117
2040	17,500	262
2041	22,197	333
2042	21,481	322
2043	34, 093	511
2044	48,851	733
2045	74,594	1,119
2046	107,093	1606
2047	69,964	1,050

4.4 Material Recovery Potential

Recycling EOL lithium-ion batteries enables recovery of critical materials such as nickel, cobalt, and lithium, supporting a circular economy. Recovery rates are estimated at 400 g/kWh (nickel), 116 g/kWh (cobalt), and 73 g/kWh (lithium) (Akram and Abdul-Kader, 2021). Using an average battery capacity of 60 kWh and EOL battery volumes, total material recovery from 2039-2047 is calculated and presented in Table 6.

Table 6. Material Recovery

Year	Batteries Recycled	Total (kWh)	Nicke (Tons)	Cobalt (Tons)	Lithium(Tons)
2039	18,712	1,122,720	449	130	82
2040	42,069	2,524,140	1,010	293	184
2041	53,357	3,201,420	1,281	371	234
2042	51,636	3,098,160	1,239	360	226
2043	81,954	4,917,240	1,967	571	359
2044	117,430	7,045,800	2,818	817	514
2045	179,312	10,758,720	4,303	1,248	786
2046	257,436	15,446,160	6,178	1,791	1,128
2047	168,182	10,090,920	4,036	1,171	737

4.5 Policy Scenario Analysis and Comparison

This section evaluates how different policy interventions influence the performance of EV battery recycling systems in Canada by comparing three scenarios: baseline (85% collection rate), EPR (90%), and incentive-based (95%). The results presented in Table 7 highlight the direct relationship between collection efficiency and key sustainability outcomes, including recycling volumes, GHG emission reductions, and employment generation.The results for the years 2039 to 2047 are summarized in Table 7.

Table 7. Policy Scenario Analysis and Comparisons

Scenario	Registration year	Number of EV & PHEV	Battery Available for Recycling (year)	Collection Rate	End of Life LIB Weight (Tons)	GHG Reduction (Tons CO_2)	Employment Opportunities

Baseline	2017	19,696	2039	85%	6,965	25,074	104
EPR Policy	2017	19,696	2039	90%	7,374	26,547	111
Incentive-Based	2017	19,696	2039	95%	7,784	28,022	117
Baseline	2018	44,283	2040	85%	15,658	56,369	235
EPR Policy	2018	44,283	2040	90%	16,579	59,686	249
Incentive-Based	2018	44,283	2040	95%	17,501	63,000	263
Baseline	2019	56,165	2041	85%	19,860	71,496	298
EPR Policy	2019	56,165	2041	90%	21,028	75,701	315
Incentive-Based	2019	56,165	2041	95%	22,196	79,909	333
Baseline	2020	54,353	2042	85%	19,219	69,188	288
EPR Policy	2020	54,353	2042	90%	20,350	73,260	305
Incentive-Based	2020	54,353	2042	95%	21,480	77,332	322
Baseline	2021	86,267	2043	85%	30,504	109,814	458
EPR Policy	2021	86,267	2043	90%	32,298	116,274	484
Incentive-Based	2021	86,267	2043	95%	34,093	122,735	511
Baseline	2022	123,610	2044	85%	43,708	157,349	656
EPR Policy	2022	123,610	2044	90%	46,279	166,606	694
Incentive-Based	2022	123,610	2044	95%	48,851	175,864	733
Baseline	2023	188,750	2045	85%	66,742	240,271	1,001
EPR Policy	2023	188,750	2045	90%	70,668	254,404	1,060
Incentive-Based	2023	188,750	2045	95%	74,594	268,538	1,119
Baseline	2024	270,985	2046	85%	95,820	344,952	1,437
EPR Policy	2024	270,985	2046	90%	101,457	365,244	1,522
Incentive-Based	2024	270,985	2046	95%	107,093	385,535	1,606
Baseline	2025	177,034	2047	85%	62,599	225,356	939
EPR Policy	2025	177,034	2047	90%	66,282	238,614	994
Incentive-Based	2025	177,034	2047	95%	69,964	251,870	1,050

Table 7 shows that higher collection rates increase EOL battery recovery, rising from 6,965 tons (baseline) to 7,784 tons (incentive based) in 2039, with stronger growth after 2043, highlighting the need for scalable recycling infrastructure. Policy interventions also improve GHG reductions (344,952 to 385,535 tons CO_2 by 2046) and employment (1,437 to 1,606 jobs), demonstrating both environmental and socio-economic benefits. Overall, EPR and incentive based policies significantly enhance recycling performance, emphasizing the importance of integrated policy frameworks for a sustainable circular EV battery ecosystem in Canada.

4.6 Contributions to Sustainable Development Goals (SDGs)

Recycling EOL EV batteries in Canada contributes to SDG 8 and SDG 13. For SDG 8, recycling generates significant employment across collection, dismantling, and processing, peaking at about 1,606 jobs in 2046, thereby supporting economic growth and skill development. For SDG 13, recycling leads to substantial GHG emission reductions, reaching approximately 385,535 tons CO_2 equivalent in 2046, contributing to lower carbon emissions and supporting Canada's transition to a net-zero economy.

4.7 Recommendations

Based on the study findings, including rising end-of-life (EOL) battery volumes, significant GHG reduction potential, and strong employment gains under higher collection efficiency scenarios, the following recommendations are proposed:

1. Policymakers

- Strengthen EPR policies to improve collection and recycling efficiency.
- Introduce performance based incentives to achieve higher recovery rates (up to 95%).
- Plan phased investment in national recycling infrastructure aligned with projected EOL growth (2039-2047).
- Integrate LIB recycling targets into national climate goals and SDGs 8 and 13.
- Enhance public awareness to improve battery return rates.

2. Industry and Recycling Operators

- Optimize collection and logistics networks through regional recycling hubs.
- Scale advanced recycling technologies (hydrometallurgical and pyrometallurgical) to improve material recovery.
- Develop workforce skills for safe dismantling and processing.
- Strengthen second-life applications to reduce recycling pressure peaks.

3. Automotive and Battery Industry

- Promote design-for-recycling through modular and standardized battery designs.
- Develop closed-loop supply chains for reintegrating recovered materials.
- Support second-life battery deployment to maximize lifecycle value.

4. Researchers and Developers

- Develop predictive models for long-term EOL battery forecasting.
- Incorporate uncertainty and sensitivity analysis in future studies.
- Extend the current framework to include behavioral and market dynamics.

Overall, these recommendations support improved system performance, consistent with findings showing that higher collection efficiency significantly increases material recovery, GHG reductions (up to 385,535 tons CO_2), and employment generation (up to 1,606 jobs).

4.8 Sensitivity Analysis

The sensitivity analysis results are presented in Table 8.

Table 8. Sensitivity Analysis of LIB Recycling under Collection Efficiency and Battery Capacity

year	Scenario	Battery Capacity (kWh)	Battery Weight (Tons)	EV& PHEV Registrations	EOL LIB Year	β	EOL LIB Available for Recycling	EOL LIB Weight (Tons)	Cobalt (Tons)	Nickel (Tons)	Lithium (Tons)	GHG Reduction (Tons CO_2	Employment (Jobs)
2017	Low	40	0.267	19,696	2039	0.95	18,711	4,996	86.8	299.3	54.6	17,986	75
2017	Base	60	0.416	19,696	2039	0.95	18,711	7,784	130.2	449.1	82	28,022	117
2017	High	100	0.667	19,696	2039	0.95	18,711	12,480	217.0	748.4	136.6	44,928	187
2018	Low	40	0.267	44,283	2040	0.95	42,069	11,232	195.2	673.1	122.8	40,435	168
2018	Base	60	0.416	44,283	2040	0.95	42,069	17,501	293.0	1010	184.3	63,000	262

2018	High	100	0.667	44,283	2040	0.95	42,069	28,060	488.0	1682.8	307.1	101,016	421
2019	Low	40	0.267	56,165	2041	0.95	53,357	14,246	247.6	853.7	155.8	51,286	214
2019	Base	60	0.416	56,165	2041	0.95	53,357	22,197	371	1281	234	79,909	333
2019	High	100	0.667	56,165	2041	0.95	53,357	35,589	618.9	2134.3	389.5	128,120	534
2020	Low	40	0.267	54,353	2042	0.95	51,635	13,787	239.5	826	151	49,633	207
2020	Base	60	0.416	54,353	2042	0.95	51,635	21,480	360	1239	226	77,332	322
2020	High	100	0.667	54,353	2042	0.95	51,635	34,441	599	2065.4	376.9	123,988	517
2021	Low	40	0.267	86,267	2043	0.95	81,954	21,882	380.3	1311.3	239.3	78,775	328
2021	Base	60	0.416	86,267	2043	0.95	81,954	34,093	571	1967	359	122,735	511
2021	High	100	0.667	86,267	2043	0.95	81,954	54,663	950.7	3,278.3	598.3	196,787	819
2022	Low	40	0.267	123,610	2044	0.95	117,430	31,354	545.0	1878.9	342.9	112,874	470
2022	Base	60	0.416	123,610	2044	0.95	117,430	48,851	818	2,818	514	175,864	735
2022	High	100	0.667	123,610	2044	0.95	117,430	78,326	1362.2	4697.2	857.2	281,974	1,175
2023	Low	40	0.267	188,750	2045	0.95	179,313	47,877	832.0	2,869	523.6	172,357	718
2023	Base	60	0.416	188,750	2045	0.95	179,313	74,594	1248	4,303	786	268,538	1,119
2023	High	100	0.667	188,750	2045	0.95	179,313	119,602	2,080	7,172.5	1,309	430,567	1,794
2024	Low	40	0.267	270,985	2046	0.95	257,436	68,735	1,194.5	4119	751.7	247,446	1,031
2024	Base	60	0.416	270,985	2046	0.95	257,436	107,093	1,791	6,178	1,128	385,535	1,606
2024	High	100	0.667	270,985	2046	0.95	257,436	171,710	2,986.3	10,297.4	1,879.3	618,156	2,576
2025	Low	40	0.267	177,034	2047	0.95	168,182	44,905	780.4	2,690.9	491.1	161,658	674
2025	Base	60	0.416	177,034	2047	0.95	168,182	69,964	1171	4,036	737	251,870	1,050
2025	High	100	0.667	177,034	2047	0.95	168,182	112,177	1,951	6,727.3	1227.7	403,837	1,683

The sensitivity analysis results in Table 8 show that LIB recycling outcomes are highly sensitive to battery capacity under a constant collection efficiency of 95%. Although the number of batteries available for recycling remains unchanged, larger battery capacities increase EOL battery mass, resulting in greater material recovery, GHG emission reductions, and employment generation. For the 2024 cohort, EOL LIB weight increases from 68,735 tons in the Low scenario to 171,710 tons in the High scenario. Correspondingly, cobalt recovery increases from 1,194.5 to 2,986.3 tons, nickel from 4,119.0 to 10,297.4 tons, and lithium from 751.7 to 1,879.3 tons. GHG emission reductions rise from 247,446 to 618,156 tons CO_2, while employment increases from 1,031 to 2,576 jobs. Overall, the results highlight that larger battery capacities substantially enhance material recovery, environmental benefits, and job creation, reinforcing the need for efficient collection systems and expanded recycling infrastructure.

4.9 Comparative Analysis

A comparative analysis of this study has been conducted with existing literature to validate the model assumptions, results, and overall findings, confirming the reliability and consistency of the proposed research framework and presented in Table 9.

Table 9. Comparative Analysis

Aspect	This Study (ABM Results)	Findings from Existing Research	Validation Outcome	References
Battery Lifecycle	20-22 years total lifecycle (10-12 years EV use + 10 years second-life)	EV battery life: 12 years; second life:10 years	Strong agreement with literature; lifecycle assumption is realistic	Akram & Abdul-Kader (2021, 2024); Foster et al.

				(2014); Malhi (2020)
EOL Battery Growth	Peak EOL battery volume 107,000 tons by 2046	Studies show rapid increase in EOL batteries between 2040-2047 due to EV growth	Trend and timing are consistent with global projections	Slattery et al. (2024); Yu et al. (2022)
Battery Retirement Function f(t-i)	Time-lag function (22-year delay) representing lifecycle transition	Lifecycle based delay modeling widely used in battery flow studies	Valid approach for long-term system modeling	Chen et al. (2019); Slattery et al. (2024)
Material Recovery (Ni, Co, Li)	Ni highest, followed by Co and Li; proportional to battery capacity	Similar recovery hierarchy and proportional scaling reported	Consistent with material composition and recovery studies	Akram & Abdul-Kader (2023, 2025); Zeng et al. (2022); Biswal et al. (2024)
GHG Reduction Factor	3.6 tons CO_2 per one ton of recycled LIB	Reported range: 2.7-4.6 kg CO_2 per kg LIB recycled	Falls within accepted range; environmentally valid	Goyal (2025); ICCT (2018)
GHG Reduction Results	Up to 385,535 tons CO_2 reduction by 2046	Recycling significantly reduces emissions from raw material extraction	Trend matches literature; benefits scale with recycling volume	Chen et al. (2019); EuRIC (2020)
Employment Generation	15 jobs per 1000 tons; peak 1,606 jobs by 2046	Recycling sector is labor-intensive, especially in collection, sorting, testing dismantling	Consistent with circular economy job estimates	Drabik & Rizos (2018); Akram & Abdul-Kader (2020)
Policy Impact (β)	Higher β (0.85→0.95) increases recycling, GHG reduction, and jobs	EPR and incentives improve collection efficiency and recovery rates	Strong agreement with policy effectiveness studies	Zhao & Kaur (2025); Slattery et al. (2024)
System Level Modeling (ABM)	Integrates lifecycle, policy, environmental, and socio-economic impacts	Most studies focus on technical or environmental aspects only	Provides broader system level contribution	Beaudet et al. (2020); Rehman et al. (2025)

The results align with existing literature on EV battery lifecycle, recycling potential, and policy impacts. The projected 20-22-year battery lifespan and the post-2040 surge in EOL batteries are consistent with prior studies. Material recovery patterns (Ni, Co, Li), as well as GHG reductions and employment estimates, fall within reported ranges, confirming the model's validity. Overall, the proposed ABM reliably captures key system behaviors while extending analysis through integrated policy scenarios.

5. Conclusion

This study developed an ABM framework to evaluate the environmental, economic, and resource recovery potential of LIB recycling in Canada using EV and PHEV registration data from 2017-2025. The results indicate a substantial increase in EOL battery volumes, reaching approximately 107,093 tons by 2046, highlighting the growing need for scalable recycling infrastructure.

The findings demonstrate significant environmental and socio-economic benefits from LIB recycling. Under higher collection scenarios, GHG emission reductions reach up to 385,535 Tons CO_2, while employment generation increases to 1,606 jobs. Recovery of critical materials, including nickel, cobalt, and lithium, also increases substantially, supporting resource security and circular economy objectives. Policy scenario analysis shows that EPR and incentive-based approaches outperform the baseline scenario, with incentive-based policies achieving the highest recycling rates and associated benefits.

A sensitivity analysis varying collection efficiency (β = 0.85-0.95) and battery capacity (40-100 kWh) demonstrates stable and monotonic trends across all outputs, indicating the robustness of the model under plausible parameter variations. However, several limitations should be acknowledged. The model is deterministic and relies on scenario based assumptions regarding battery lifetime, capacity, weight, collection efficiency, and loss rates. Direct validation and stochastic calibration are constrained by the limited availability of historical LIB recycling data in Canada. In addition, future developments in battery chemistries, including increased adoption of LFP batteries and emerging solid state technologies, may influence recycling performance and material recovery patterns.

Despite these limitations, the proposed framework provides valuable insights into the long term implications of EV battery recycling in Canada and offers a useful decision support tool for policymakers and industry stakeholders. Future research should incorporate stochastic modeling, uncertainty quantification, empirical validation, and chemistry specific battery pathways to further enhance the accuracy and applicability of the model.

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