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Research article

Evaluating circular economy strategies for raw material recovery from end-of-life lithium-ion batteries: A system dynamics model

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ABSTRACT

Across the globe, with the increasing emphasis on decarbonization, lithium-ion battery (LIB) demand for mobility (which serves as a power source for electric vehicles) and stationary energy storage sector (SESs) increases, which generates a large stock of end-of-life (EOL) LIBs. Continually increasing the stock of EOL LIB having different LIB variants necessitates the development of efficient circular economy (CE) strategies (recycling and repurposing) to recover raw materials contained in them. Focusing on different CE strategies, we develop a system dynamics model to address the complexity of the raw material recovery process by analyzing the interrelationship between collection rate (government), EOL LIB variant mix (consumer preference), and EOL LIB allocation to recycling and repurposing (Battery OEMs). Our analysis reveals that a high EOL collection rate and recycling reduces the raw material (Lithium (Li), Nickel (Ni), and Cobalt (Co)) demand by 2%–17% based on LIB variant proportion in EOL LIB stock. We observe thrice higher Co recovery and 1.5 times higher Ni recovery in material-rich battery chemistries as compared to others. Repurposing delays the raw material recovery but reduces LIB's demand for SESs. In addition, we observe that the repurposed EOL LIB supply increases the recyclable EOL LIB supply by 0.027–0.2 million units at the end of 2030. Hence, it is imperative for emerging economic countries like India, with scarce strategic raw materials sources and increasing demand for LIB from mobility and SES sectors, to frame policies that incentivize the collection and EOL handling process infrastructure and prioritize between recycling and repurposing of EOL LIBs.

1. Introduction

Mobility transitions have become the focus of practitioners and scholars with a growing emphasis on the decarbonization of transportation systems (Abergel et al., 2020; Bibra et al., 2022). The proliferation of electric vehicles (EVs) in the transportation sector is imperative to induce a paradigm shift in the mobility sector, as EVs are considered zero-tailpipe emission vehicles. Batteries power EVs, and among all commercially available batteries, LIBs are most suitable to power EVs based on their superior performance characteristics (Nitta et al., 2015; Schmuch et al., 2018). Global LIB demand is forecasted to grow by 30%–35% to reach 4.7 terawatt-hours (TWh) in 2030 (Fleischmann et al., 2023). LIB demand from the automotive sector and stationary energy storage (SES) contribute 70%–80% of global LIB demand.

Growing demand for LIBs generates a large pool of end-of-life (EOL) LIB when LIB nominal capacity reaches 80% of its original capacity (Goodenough, 2012; Morse, 2021). LIB life varies from 3–10 years based on driving conditions, LIB variants, charging frequency, and warranty offered by battery original equipment manufacturers (OEMs) (Richa et al., 2014; Zubi et al., 2018; Beuse et al., 2020). NITI Aayog, a strategy think tank in India, forecasted that total cumulative LIB demand from the electric mobility sector will reach 381 GWh in 2030 which will generate 70–80 GWh EOL LIB in 2030. Abergel et al. (2020) forecast that 100–120 GWh of LIBs will reach EOL in 2030 based on the difference in scenarios taken by the International Energy Agency (IEA).

EOL LIBs are collected from the consumers and transported to different locations for further processing. EOL LIBs are transported through various means, like trucks, ships, etc., to other sites based on processing facility location, ease of processing, and favorable government policies (Schulz-Mönninghoff and Evans, 2023; Lander et al., 2021; Slattery et al., 2021). The collection rate depends on the efficiency of

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collection processes (Vlachos et al., 2007), mode of transportation, and government regulations (Jacoby, 2019; Dunn et al., 2022).

Collected LIB undergoes stringent quality checks based on the state of health (SOH), state of charge (SOC), etc., of LIB before allocation to different circular EOL management processes like remanufacturing, repurposing, and recycling (Chirumalla et al., 2023). Remanufactured EOL LIB undergoes stringent quality checks before being reused in EVs (Albertsen et al., 2021; Chirumalla et al., 2023; Schulz-Mönninghoff and Evans, 2023). Due to lack of standard quality check methods and regulations, we only consider the recycling and repurposing process for managing EOL LIB. EOL LIB can be either recycled to obtain critical raw materials like lithium (Li), cobalt (Co), and nickel (Ni) (P. Ryan; The Economist, May 13, 2021), or it can be repurposed as second-use LIB for other applications (D. Holger et al.; The Wall Street Journal, June 13, 2022) like stationary storage systems, frequency regulation, renewable integration, etc., (Chen et al., 2019; Liu et al., 2020; White et al., 2020; Dunn et al., 2022).

Raw material recovery from EOL LIB through recycling depends on the recycling process efficiency (Dunn et al., 2022; Liu et al., 2023), battery mix in total LIB demand (Jiang et al., 2021; Kamath et al., 2023), LIB capacity (Shafique et al., 2023), and recycling capacity (Georgiadis and Athanasiou, 2013), whereas the quality of collected EOL LIB, maturity of the repurposing process, demand for repurposed LIB, and repurposing capacity impact the LIB second-use (Vlachos et al., 2007; Schulz-Mönninghoff et al., 2021; Dunn et al., 2022; Alšauskas et al., 2024). Repurposing enables EOL LIB's use in cascade application (Bobba et al., 2019) and improves the LIB life but, at the same time, it delays the recycling process which soars the demand for the virgin raw material.

Along with this, varying collection rates due to the nascent stage of growth of the collection infrastructure (Georgiadis and Besiou, 2010; Rizova et al., 2020), LIB variant mix in continually increasing EOL LIB stock (Dunn et al., 2022), lack of government policies (Alsauskas et al., 2023; Alšauskas et al., 2024), and EOL LIB handling infrastructure (Georgiadis and Athanasiou, 2013) bring complexity in planning and managing different EOL recovery strategies. The factors mentioned above interact with each other through a nonlinear multiloop feedback system, and the delay in realization of the impact of interacting among variables on raw material recovery adds further complexity in the allocation of EOL LIB to different EOL LIB handling process. Therefore, in-depth analysis is required to explore the tradeoff between EOL LIB handling processes impacted by EOL LIB collection rate and infrastructure, battery mix of EOL LIB, and EOL LIB handling infrastructure. Hence, we develop a system dynamics (SD) model to understand the complexity of recovery of raw material from EOL LIB by conducting a brief analysis among the following directions:

- How does variation in EOL LIB collection rate impact the raw material recovery from EOL LIB?
- How will the consumer preferences for LIB variants impact the recovery of strategic raw material from EOL LIB?
- How does the priority in allocating collected EOL LIB for LIB recycling and repurposing impact the raw material recovery market?

The system dynamics methodology is widely used for understanding the complexity of raw material recovery from EOL vehicles and LIBs by using different circular management strategies (Georgiadis and Besiou, 2010; Georgiadis and Athanasiou, 2013; Bobba et al., 2018b; Alamerew and Brissaud, 2020; Mohan and Amit, 2021; Weigl and Young, 2023; Kamath et al., 2023). To the best of our knowledge, this is the first attempt to apply the system dynamics model to analyze the trade-off between circular economy strategies' impact on raw materials recovery from EOL LIB with varying collection rates and different LIB proportions in EOL LIB stock. We consider the impact of varying LIB variant proportions in EOL LIB stock, minimum collection ratio, and impact of tradeoff of allocation different ratio of EOL LIB to recycling and repurposing on raw material recovery and availability of repurposed LIB. The model results highlight that raw materials recovery from EOL LIBs increased by twice when the collection rate of EOL LIBs increased from 50% to 90%. Increasing the proportion of lithium iron phosphate (LFP) batteries in collected EOL LIB reduces the recovery of strategic raw materials Li, Ni, and Co from the EOL LIB as LFP does not contain Ni and Co. Co recovery is three times, and Ni recovery is around 1.5 times higher in high cobalt scenarios compared to LFP scenarios. Apart from this, improving the repurposing of EOL LIBs minimizes the demand for new LIBs for stationary energy storage but reduces the raw material recovery, as repurposing extends the LIB life. Repurposed LIB variant availability depends on the battery mix of EOL LIB, repurposing infrastructure, and EOL LIB collection rate. Recyclable LIB supply increased from EOL repurposed LIB supply (depends on repurposed LIB life in different appliances), which improves the raw material recovery that eases the pressure on exploring new raw material mines to fulfill the increasing demand for the booming electric mobility market.

This paper is organized as follows: Section 2 reviews the literature on the circular economy strategy used for managing EOL LIB and raw material recovery. Section 3 details the system dynamic model. Section 4 discusses the simulation results, and Section 5 provides a discussion of the results. Section 6 concludes the paper.

2. Literature review

EOL LIB can be recycled to obtain valuable raw materials or be used as a second life LIB as EOL LIB landfill pollutes the environment and is hazardous to human beings. This section focuses on literature related to different circular economy strategies for managing EOL LIB. We also discuss the literature on the usefulness of system dynamics in managing the complex EOL LIB recovery management system that helps in raw material recovery.

2.1. Circular economy strategies for LIB

According to the waste management hierarchy, repair, remanufacturing, repurposing, and recycling are widely used circular economy (CE) strategies for handling EOL LIB. In remanufacturing and repurposing, cells or modules that lose 80% of their nominal capacity are replaced with new cells or modules in the battery pack (repurposing needs change in battery management system based on applications) and then used other applications (Chen et al., 2019; Schulz-Mönninghoff and Evans, 2023). Remanufactured LIB undergoes strict quality checks before use in EV. Recycling helps extract raw materials from EOL LIB, reducing the demand for virgin raw materials for LIB. A detailed explanation of repurposing, recycling, and the impact of tradeoffs between recycling and repurposing raw material recovery is explained below.

2.1.1. LIB recycling

Physical materials separation, pyrometallurgical recovery, hydrometallurgical, direct recycling, and biological metals reclamation are commonly used for LIBs recycling (Chen et al., 2019; Harper et al., 2019; Chen et al., 2022; Makwarimba et al., 2022). In Pyrometallurgical recycling, LIBs are fed to a high-temperature furnace where the burning of electrolytes and plastic in the batteries provides heat; graphite/carbon and aluminum are oxidized; Co, Ni, copper (Cu), and iron is recovered as matte, and the rest of the materials end as slag. Matte is further processed through acid leaching followed by solvent extraction to recover Ni and Co (Chen et al., 2019; Sommerville et al., 2021). In Hydrometallurgical recycling, EOL LIBs are shredded, and a low-temperature calcination process is used to burn binder and electrolyte. After that leaching process, solvent extraction is performed to obtain lithium carbonate, Co, and Ni compounds (Sommerville et al., 2021; Makwarimba et al., 2022). In the direct recycling process, EOL LIBs are shredded, and then several physical separation processes are applied to recover the cathode, anode, plastics, and metals. The recovered cathode then undergoes lithium replenishment in the cathode to produce a new cathode used for EVs (Chen et al., 2019; Harper et al., 2019). The hydrometallurgical process recovers Li, Co, and Ni, whereas only Co and Ni are recovered from Pyrometallurgical recovery (Gaines, 2014; Dai et al., 2019).

LIBs are recycled to obtain critical raw materials embedded in the electrodes and electrolytes when they reach EOL (Harper et al., 2019; Kamran et al., 2021). Hence, it reduces the EOL LIB landfills and eases pressure on new raw materials mines needed to cater to rising LIB demand (Chen et al., 2019). Shafique et al. (2022) use multidimensional scenario analysis to predict the quantity of recovered Li, Ni, and Co in China and the U.S.. Authors state that in 2030, 5–7 kilotons (kt) Li, 35–60 kt Ni, and 4–6 kt Co are recovered from EOL LIB in China, whereas in the U.S., 2.3–2.6 kt Li, 16–26 kt Ni, and 3–4 kt Co is recovered. Liu et al. (2023) explores that recycling of EOL LIB will cover 27.4–42.0% Li, 50.4–77.5% Co, and 50.4–77.6% Ni demand for new LIBs. Zeng et al. (2022) develop different scenarios for analyzing the impact of secondary raw materials on primary raw material demand. The authors forecast that total secondary Co stock would reach 3680 kt in 2020–2050.

2.1.2. Repurposing of LIBs

EOL LIBs are repurposed after stringent quality checks. EOL LIBs are dismantled at the module or cell levels to identify defective parts. Damaged LIB parts are replaced after inspection, and a new battery management system is included in the LIB pack (based on the application) to develop repurposed LIBs (Bobba et al., 2019; Chen et al., 2019; Alfaro-Algaba and Ramirez, 2020). Repurposed EOL LIB can be used as stationary energy storage, electricity grid frequency regulation service, behind-the-meter (BTM) energy storage, load leveling, and many more applications (Heymans et al., 2014; White et al., 2020; Khowaja et al., 2022). Bloomberg New Energy Finance has estimated the potential of the global second-life batteries market is expected to be about 26 gigawatt hours (GWh) in 2025 (equivalent to about 47% of the global LIB supply in 2015). Engel et al. (2019) predict that second-life supply will vary from 117–227 GWh/year based on different scenarios. Xu et al. (2023) estimates that the cumulative capacity of the second-use battery will reach 14.8–31.5 terawatt-hours (TWh) in 2050 when the second-use battery is utilized for ten years. 4R Energy Corp repurposed EOL Nissan Leaf batteries for stationary energy storage.

Although a high volume of EOL LIBs will be available for second-use by 2050, complex and customized battery design, decreasing new LIB prices, and customer acceptance for repurposed LIBs limits the EOL LIB use as second-use LIB (Neubauer et al., 2015; Martinez-Laserna et al., 2018; Engel et al., 2019; Zhu et al., 2021). Martinez-Laserna et al. (2018) conducts a comprehensive literature review on LIB's secondary use. Engel et al. (2019) analyze factors impacting the EOL LIB repurposing. Authors state that customization of LIB based on EV models decreases cost parity among new and repurposed LIB. However, the lack of regulatory policy on LIB reuse and inadequate repurposed LIB quality assessment standards limit the EOL LIB repurposing.

2.1.3. LIB repurposing-recycling trade-offs

EOL LIB can be recycled to obtain critical raw materials like Li, Co, and Ni, or it can be second use for other applications like stationary storage systems, frequency regulation, renewable integration, etc., (Chen et al., 2019). Hence, there is always a trade-off between LIB recycling and repurposing (Krishna Mohan et al., 2021). Repurposing extends the LIB life to 5–10 years based on usage but delays the EOL LIB recycling, reducing the recycled material supply (Bobba et al., 2018a). Along with delaying the recycled material supply, the recycling-repurposing trade-off has different economic impacts. Li et al. (2018) develop a Mixed integer nonlinear programming (MINLP) model to analyze the impact of integrating remanufacturing and recycling infrastructure to a standalone LIB manufacturing facility on supply chain profit. The authors state that including remanufacturing will enhance supply chain profit by 30.93% for a standalone manufacturing facility and 9.81% for an integrated manufacturing-recycling facility. Jiang et al. (2021) develop a Material flow analysis model to analyze the economic impact of cascade utilization and material recovery (through recycling only). The authors find that cascade utilization of EOL LIB creates a monetary value of 147.8 billion US dollars (USD) by 2040, twice the value (76.9 billion USD) created through only material recovery. Reinhardt et al. (2019) suggests that the high costs issue with LIBs can be partly resolved through the LIBs' second use that enables the development of less-energy-intensive storage systems, prolonging the battery life and closing the resource loop.

2.2. System dynamics modeling

Multiple stakeholders are involved in EOL LIB recovery strategies. They are involved in each stage of the recovery process, from the collection of EOL LIB to recycling EOL LIB to get recycled products. All the stages are interlinked, and different factors impacting different stages are interconnected, bringing complexity to different recovery processes. The system dynamics modeling methodology developed by Prof J. W Forrester is a widely used methodology to analyze the complex system (Abbas and Bell, 1994; Berends and Romme, 2001; Georgiadis and Besiou, 2008; Feng et al., 2013; Wang et al., 2014; Nieuwenhuijsen et al., 2018; Pratap et al., 2019; Bhanu et al., 2024; Pratap et al., 2023). Wang et al. (2014) develop a system dynamics model to analyze the impact of passenger car life span on EOL vehicle waste in Belgium. The authors find that the ELV reuse and recovery rate increases with a decreasing passenger car life span. Li et al. (2023) build a system dynamics model to analyze the impact of subsidy on EV sales. Authors state that under static subsidy scenarios, acquisition subsidy has a higher influence on EV sales than R&D subsidy, but under fixed subsidy budget, R&D subsidy has a more significant impact on EV sales than acquisition subsidy. Li et al. (2020) uses a game-based system dynamics model to analyze the effect of a deposit-refund scheme on EV recycling. The authors identify that the collection rate of used EVs increases with an increase in the deposit-refund scheme but is constrained by government subsidy budget allocation. Model results highlight that consumers' environmental awareness increases the collection rate of used EVs.

2.3. Overview of relevant literature

In summary, many studies present different methods of LIB recycling, their impacts on raw material recovery, and the economic impact of LIB recycling. Similarly, studies related to repurposing explain the impact of repurposing on the availability of repurposed LIB for secondary use and the financial benefits of repurposing. Table 1 provides an overview of the literature relevant to our paper. Table 1 highlights that only a few studies focus on exploring the tradeoff between recycling and repurposing on raw material recovery and availability of second-use LIB, EOL repurposed LIBs impact on raw material recovery, the effect of delay on collection, recycling, and repurposing infrastructure on raw material recovery, and impact of charging frequency on LIB replacement. Along with the dilemma of recycling and repurposing and the lack of infrastructure, different LIB variant adoption by consumers and raw material composition in LIB variants impact raw material recovery. This study takes a holistic approach backed by SD modeling to explore the impact of the tradeoff between recycling and repurposing on variability in raw material recovery for EOL LIB. This study also examines the time delay impact on infrastructure development, variable collection rate, varying LIB variants market share, and raw material composition in LIB variants impact on raw material recovery.

Table 1
Overview of the most relevant literature.

Author	Method	Battery type	Materials accessed	Circular economy strategy
Bobba et al. (2019)	Material flow analysis	NMC, NCA,	Li, Co	Remanufacturing, Repurposing, Recycling
Wasesa et al. (2022)	Hybrid simulation (Agent-based and System dynamics	NMC, NCA, LFP	Li, Ni, Co, Cu, Al	Recycling
Dunn et al. (2022)	Material flow analysis.	NCX (NMC 632, NMC 811, and NCA), LFP	Li, Co, Ni	Recycling
Kastanaki and Giannis (2023)	Material and substance flow analysis	NCA, LMO, LFP, NMC 111, NMC 532, NMC 622, NMC 811, NMC 955	Li, Co, Ni, Cu	Remanufacturing, Reuse, Recycling
Shafique et al. (2023)	System dynamics model	NMC, NCA, LFP	Li, Ni, Co, Cu	Recycling
Liu et al. (2023)	Stock driven model	LCO, NMC, NCA, LMO	Li, Co, Ni, Mn, Cu, Al, Fe	Recycling
Schulz-Mönninghoff and Evans (2023)	Inductive research approach	NMC	Li, Ni, Mn, Co	Repurposing
Chirumalla et al. (2023)	Multi-faceted approach	Lithium-ion battery	Focused on second life use of LIB	Remanufacturing, Repurposing, Reuse

3. Methods

In this section, we provide the details of the system dynamics model used in our study. Section 3.1 explains the market setting and provides theoretical support for the system dynamics model developed. Section 3.2 gives the scope of the problem, describes the various relationships identified in the system, provides the system dynamics model, and explains the various decision rules that govern the model.

3.1. Market setting

Battery manufacturers are always in a dilemma in EOL LIB allocation for recycling or repurposing when LIB reaches EOL. EOL LIBs allocation to different recovery processes depends on variables like battery collection rate, battery quality, recycling process efficiency, repurposing efficiency, minimum collection quantity, etc. Interconnection and dependency among the abovementioned variables complicate the LIBs recovery process. In our model, government regulations, EOL LIB collection capacity, and recovery process profitability impact the quantity allotted to the recycling process and second use. Collected EOL undergoes a decision process that decides the quantity allotment for recycling and second use. The leftover EOL LIB is sent to the landfill. The quantity allotment to recycling and second use affects the raw material recovery from EOL LIB, process profitability, demand for virgin raw material, and EOL LIB ending as a landfill.

3.2. System dynamics modeling

System dynamics models are a widely used methodology for exploring a complex system involving strategic recycling and repurposing decisions (Georgiadis and Besiou, 2010; Alamerew and Brissaud, 2020; Kamath et al., 2023; Li et al., 2023). Hence, we develop a system dynamics (SD) model to study the trade-offs between EOL LIB recycling and second-use and its impact on raw material recovery and the LIB market. SD modeling consists of various steps, which consist of defining model scope, identifying the causal relationship among variables linked through a multi-loop feedback system, developing of stock and flow (simulation model diagram, and testing the model accuracy and validity.

Table 2
Vensim subscripts description.

S. No.	Name	Description	Elements
1	Battery	Lithium-ion battery Variants	NMC622; NMC811; NCA; LFP
2	Battery Mix	Battery proportion under consideration	NMC622 ratio (BR1); NMC811 ratio (BR2); NCA ratio (BR3); LFP ratio (BR4)
3	Raw material	Chemical composition of electrodes	Lithium (Li); Nickel (Ni); Cobalt (Co)
4	Recycling efficiency	Raw material recycling efficiency	Lithium (RE1); Nickel (Ni); Cobalt (RE2)
5	Raw material price	Price of raw material used in LIB electrodes	Lithium (Lip); Nickel (Nip); Cobalt (Cop)

3.2.1. Scope of the model

In this section, we mainly focus on defining model boundaries. As the model explores the impact of the tradeoff between the allocation of EOL LIB to recycling and repurposing, which are predominant in emerging economies, we use data from an emerging economy, i.e., India. We consider EVs of a homogeneous nature (battery electric cars (BEC)) and stationary energy storage (SES) for energy storage for household applications demand for the Indian market. We consider BES and SES devices as they contribute around 80% of total LIB demand (Alsauskas et al., 2023; Alšauskas et al., 2024). We use the subscript option in Vensim® Pro Software (Version 6.4E) to assign values to different raw materials and batteries. All the values are calculated every month. Battery ratio is the same for EV sales, SES, collected EOL LIB, recycled LIB, and repurposed LIB. We assume that the demand for LIBs is equivalent to the sales of BECs and SESs. Different LIB variants' demand is calculated by multiplying initial BEC and SES sales by the battery ratio. We use subscripts for variables that enable repetitions of variables without cluttering the model, as subscripts do not appear in sketches (Harrison et al., 2016). Five subscript ranges are represented in the model shown in Table 2. We have summarized the parameter values used to develop the different scenarios in Table 3.

3.2.2. Causal loop diagram

The causal loop diagram (CLD) provides a macro-level representation of the interactions in the system. A causal loop diagram (CLD) acts

Table 3
Scenarios used in the System dynamics model.

Model input	Scenarios
Cathode chemistry sales	Three scenarios taken from International Energy Agency (IEA) EV outlook report defined in Table 4 (Source: Alsauskas et al. (2023), Alšauskas et al. (2024))
Percentage repurposed	Varies from 10%–90% (Model assumption)
Percentage recycled	Varies from 10%–90% (Model assumption)
Collection rate	Varies from 10%–90% (Model assumption)
Raw material composition	Defined in Table 5 (Source: Olivetti et al. (2017))

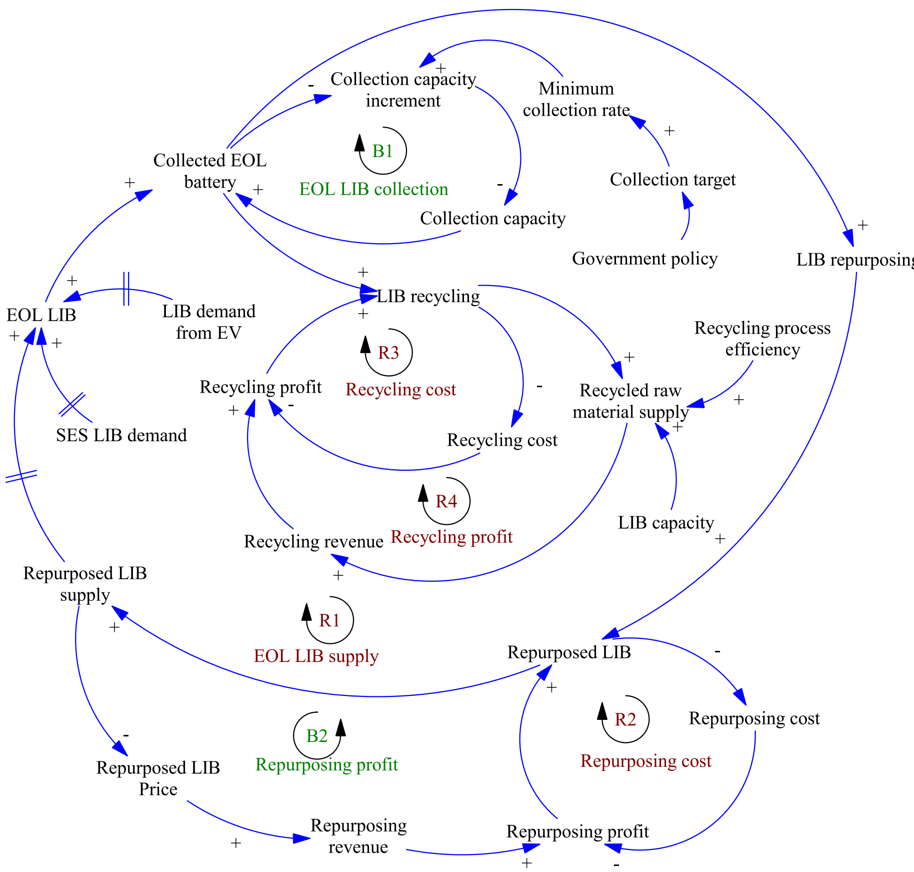


Fig. 1. System dynamics model: Causal loop diagram.

as a visual tool that assists in developing the pictorial representation of a dynamically complex system containing multi-loop, feedbacks, delays, and non-linearity (Senge and Sterman, 1992; Ford, 1999; Vlachos et al., 2007; Sterman, 2010). Model complexity arises due to interconnection and interrelationships among variables that explain model behavior. Model variables are interlinked by a causal linkage and act as feedback in the system (Wolstenholme and Coyle, 1983; Berends and Romme, 2001; Kunc and Morecroft, 2007; Ford, 2018). CLD has three main components: causal links (shown by arrows) that explain the relationship among variables, and loop polarity represented by positive (+) or negative (−) signs that help identify loop polarity. It indicates the change in the dependent variable with respect to the independent variable when all other variables are kept constant, and the loop identifier helps identify the nature of the loop – balancing or reinforcement.

In this section, we explore the causal relationship among variables using a CLD that provides the theoretical background for developing the system dynamics model. Minimum collection rates defined by the government, collection capacity, recycling and repurposing capacity, and battery mix are variables interlinked to create a dynamically complex system containing feedback and delays impacting raw material demand.

Fig. 1 shows the causal loop diagram (CLD) to understand the impact of different EOL LIB recovery strategies on raw material demand. CLD represents the causal relationships between various variables in the system. We identify six feedback loops in the system: balancing loops – “EOL LIB collection”, “Repurposing profit” and reinforcement loop – “EOL LIB supply”, “Repurposing cost”, “Recycling cost”, “Recycling cost”.

- **Balancing loop, B1 - *EOL LIB collection*:** Collected EOL battery $\uparrow \Rightarrow$ Collection capacity increment $\downarrow \Rightarrow$ Collection capacity $\downarrow \Rightarrow$ Collected EOL battery $\downarrow$
  EOL LIBs are collected through different modes of transportation before processing through different EOL management practices- recycling and repurposing (Lander et al., 2021; Schulz-Mönninghoff and Evans, 2023). The collection of EOL LIB depends on collection capacity (Vlachos et al., 2007). Enhancement of collection capacity leads to an increment in the collected quantity that reduces the landfill, which reduces the harmful

impact of dumping the EOL LIB in open areas (Georgiadis and Athanasiou, 2013).

- **Balancing loop, B2 - *Repurposing profit*:** Repurposed LIB supply ↑ ⇒ Repurposed LIB price ↓ ⇒ Repurposing revenue ↓ ⇒ Repurposed profit ↓ ⇒ Repurposed LIB ↓ ⇒ Repurposed LIB supply ↓
An increase in collection capacity enhances the LIB repurposing (depending on the quality of the collected EOL LIB), which increases the repurposed LIB supply (Georgiadis and Athanasiou, 2013; Chirumalla et al., 2023). As the supply of repurposed LIB increases, the price of repurposed LIB decreases (due to scaling effects). The reduction in repurposing LIB price reduces the repurposing revenue, which reduces profitability, leading to further capacity contraction and, consequently, less LIB repurposing. The supply of repurposed LIB falls alongside the reduction in repurposing activities.
- **Reinforcement loop, R1 - *EOL LIB supply*:** EOL LIB ↑ ⇒ Collected EOL LIB ↑ ⇒ LIB repurposing ↑ ⇒ Repurposed LIB ↑ ⇒ Repurposed LIB supply ↑ ⇒ EOL LIB ↑
EOL LIB collection increases with the increasing EOL LIB availability to reduce the EOL LIB landfill (Chen et al., 2019). Collected EOL LIBs are used as repurposed LIBs after the stringent quality check of collected LIBs. Increasing repurposing (utilization of repurposed capacity) enhances the repurposed LIB supply. Repurposed LIB reaches the EOL stage after some time delay (based on application) and grows the EOL LIB availability (Schulz-Mönninghoff and Evans, 2023).
- **Reinforcement loop, R2 - *Repurposing cost*:** Repurposed LIB ↑ ⇒ Repurposing cost ↓ ⇒ Repurposed profit↑ → Repurposed LIB ↑
- **Reinforcement loop, R3 - *Recycling cost*:** LIB recycling ↑ ⇒ Recycling cost ↓ ⇒ Recycling profit ↑ ⇒ LIB recycling ↑
An increment in the availability of EOL LIB for repurposing reduces the repurposing cost. Cost reduction enhances the profitability of repurposing, resulting in more EOL LIB repurposing. Similarly, recycling costs are reduced with increased LIB recycling, leading to more profitability in the recycling process. As a result of which, more LIBs are recycled (Bobba et al., 2019; Dunn et al., 2022).
- **Reinforcement loop, R4 - *Recycling profit*:** LIB recycling ↑ ⇒ Recycled raw material supply ↑ ⇒ Recycling revenue ↑ ⇒ Recycling profit ↑ ⇒ LIB recycling ↑

LIB recycling enhances the supply of recycled raw material based on the recycling process efficiency and recycled LIB quantity (Kamath et al., 2023). Growth in the supply of recycled material increases recycling profitability by enhancing the revenue obtained from recycled material. Profitability enhancement brings more recyclers into the process, which results in growth in the recycling process.

3.2.3. Stock and flow diagram

The stock and flow diagram (SFD) helps establish mathematical relationships among model variables that assist in understanding model dynamics arising from interaction among variables defined in CLD. Fig. 2 represents the SFD that helps understand the trade-offs between recycling and repurposing. Model variables are categorized into stock, flow, and auxiliary variables. A rectangular box represents stock/state variables changed using flow variables denoted by the valve symbol. An auxiliary variable consists of stock functions, constants, or exogenous inputs. A stock variable represents a level or inventory value at a given period. The flow variables (inflow and outflow) are the rates at which stock variables change and are represented as a function of time. Clouds outside the model boundary are a source or sink of flow variables. It is assumed to have an infinite capacity and supports flow variables.

Table 4
Proportion of LIB variants in total LIB demand.
Source: Olivetti et al. (2017), Maisel et al. (2023).

S. No.	Battery variant	High Cobalt Scenario (Values in %)	High Nickel Scenario (Values in %)	LFP
1	NMC622	0.76	0.1	0
2	NMC811	0.13	0.8	0.6
3	NCA	0.11	0.1	0.1
4	LFP	0	0	0.3

Table 5
Element Requirements (Li, Co, Ni) for LIB variants (Units: kg/kWh).
Source: Olivetti et al. (2017), Kamath et al. (2023) and Maisel et al. (2023).

S. No.	Battery Chemistry	Raw material composition		
		Li	Ni	Co
1	NMC622	0.126	0.641	0.214
2	NMC811	0.111	0.75	0.094
3	NCA	0.112	0.759	0.143
4	LFP	0.084	0	0

3.3. Model variables

We classify the model variables in themes such as “EOL LIB supply” (EOL LIB calculation), “EOL LIB collection” (collection capacity adjustments), “EOL LIB recycling” (recycling costs and profit calculation), “EOL LIB repurposing” (repurposing costs and profit calculation), “Learning effect” (LIB production cost variation), and “Raw material” (raw material demand and supply). Different LIB chemistry variants such as NMC 622, NMC 811, NCA, and LFP are considered, and their proportionate demand is represented in Table 4. The change in raw material composition with changing battery variants is described in Table 5. All model variables are explained in detail in the paper’s supplementary information.

4. Results

The model is simulated for 180 months with INITIAL TIME = 0, FINAL TIME = 180, and TIMESTEP being 0.5 months results are no longer sensitive to the choice of TIMESTEP when we reduce TIMESTEP below 0.5 months). This section explores the impact of variations in LIB variants composition in EOL LIB, collection rate, and EOL LIB allocation to recycling and repurposing. In each defined scenario, we consider the initial recycling and repurposing capacity to be 100 units and the LIB capacity to be 60 kilowatts (kWh). In Scenarios 2, 3, and 4, we considered the EOL LIB collection rate as 50%. In Scenarios 1 and 2, the proportion of EOL LIB allocated to recycling is 80%. In Scenario 1, the collection capacity of EOL LIB varied between 10%–90% (based on Kamath et al. (2020), Wasesa et al. (2022)). In contrast, in Scenario 2, LIB variant proportion in EOL LIB varies based on scenarios given in Table 4. In Scenario 3 and 4, we varied the proportion of EOL LIB allocated to recycling and repurposing (10%–90%). Scenario 1 and 3–4 consider the Low Nickel Scenario of Table 4 for simulation.

4.1. Model validation

We follow multiple validation methods provided in the literature to verify the suitability and appropriateness of our model (Barlas, 1989, 1996; Thies et al., 2016). Along with this, we perform structural validity tests to gain confidence in the usefulness, applicability, and simplicity of our model, as there is currently no method available to establish the correctness of the system dynamics model (Ford and Flynn, 2005; Taylor et al., 2010; Sverdrup and Ragnarsdottir, 2016; Wasesa et al., 2022).

We perform structural validity tests to affirm the similarity of our model to a real-world system. We are confident in the structural

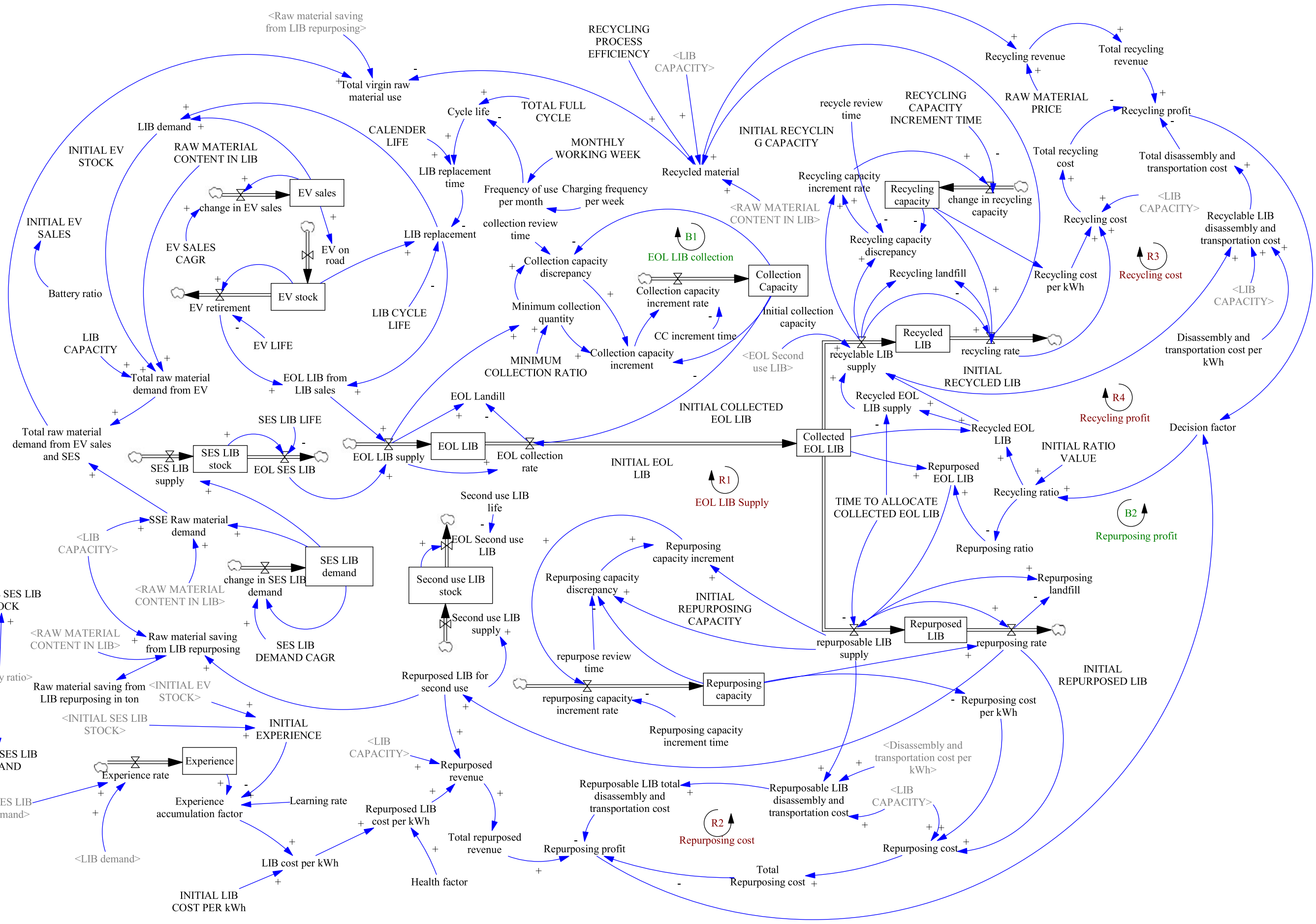


Fig. 2. System dynamics model: Stock and flow diagram.

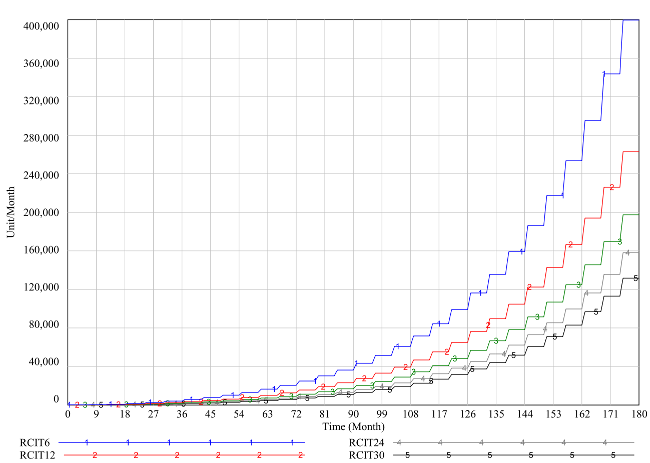


Fig. 3. Recycling capacity increment time impact on recycling capacity.

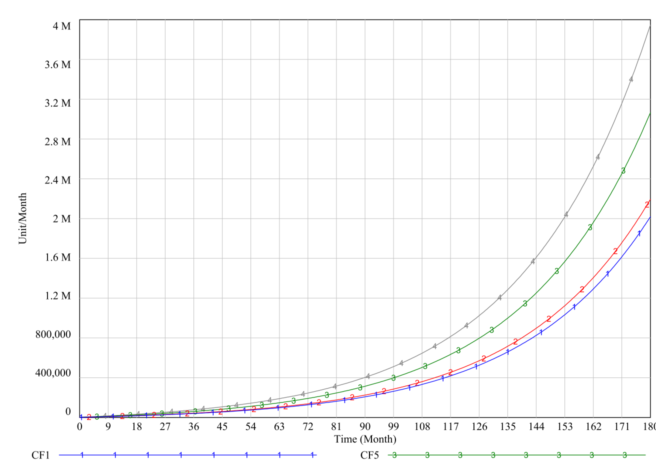


Fig. 4. Charging frequency impact on EOL LIB supply.

soundness and suitability of the model for the following reasons: (1) Our model resembles the behavior of the general structure of existing simulation models of the automotive recycling and repurposing market (Bobba et al., 2019; Dunn et al., 2022; Wasesa et al., 2022; Kamath et al., 2023; Chirumalla et al., 2023; Shafique et al., 2023). The research mentioned above highlights that a higher collection rate leads to higher raw material recovery and increases the availability of repurposed LIB. The results highlighted by them resemble the results explained in Sections 4.2, 4.3, 4.4, and 4.5. (2) The equations that establish the interconnection among the model variables are checked for their similarity with the existing literature and variables dimensional consistency. (3) Equations connecting model variables are based on well-defined theories, such as learning effect, capacity expansion, etc., defined in the literature.

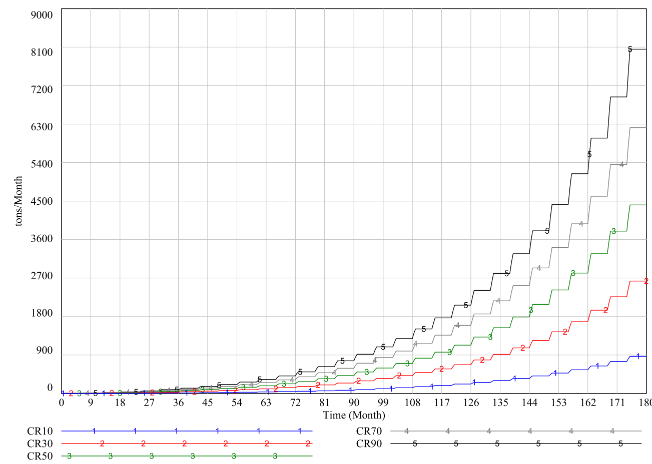
We perform a structure-oriented behavior test on the SD model by assigning extreme values to the model variables, following the approach described by Barlas (1996). This test aims to identify and uncover any structural flaws in the model. The model is tested for the following scenarios: (1) Impact of recycling capacity increment time on recycling capacity and (2) Impact of charging frequency on EOL LIB supply. In all Scenarios, we consider the average battery capacity as 60kWh for high Cobalt scenarios explained in Table 4, collection capacity is taken as 50% (only 50% of EOL LIBs are collected), and 80% of collected EOL LIB is allocated for recycling. Fig. 3 shows the variations in recycling capacity with a change in recycling capacity increment time (RCIT). RCIT varies from 6 to 30 months (RCIT6- RCIT30), where RCIT6 means six months to increase the recycling capacity, and RCIT30 means 30 months to increase the capacity. The value of RCIT for analysis is taken as “RCIT6, RCIT12, RCIT18, RCIT24, and RCIT30”. RCIT increment delays the capacity increment rate, which reduces the total recycling capacity. Fig. 3 shows that in RCIT6, recycling capacity reaches 399,600 units/month, whereas, in RCIT30, recycling capacity reaches 131,700 units/month for NMC622.

In other scenarios, the charging frequency varies between 1 and 7 cycles/week (where one cycle/week (CF1) is the minimum charging frequency, whereas seven cycles/week (CF7) is the maximum charging frequency). A lower charging frequency reduces the quantity of LIB replaced by increasing the LIB replacement time. In contrast, a high charging frequency decreases the LIB replacement time, which increases the LIB replacement by early LIB replacement. EOL LIB supply increases with an increase in LIB replacement. Hence, high replacement leads to high EOL LIB supply, as shown in Fig. 4.

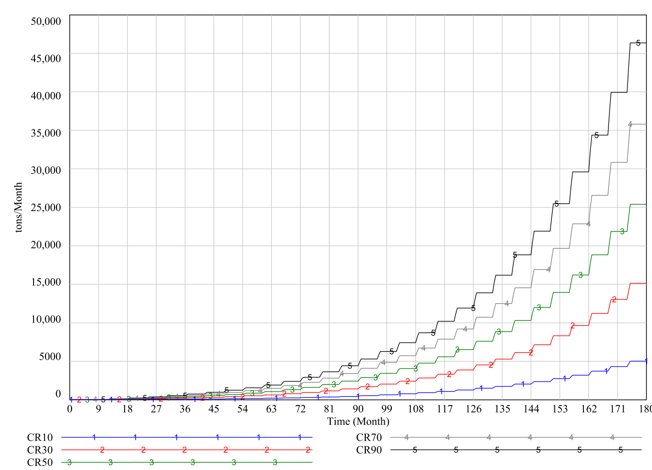
4.2. Scenario 1: Variation in EOL LIB collection rate

Collection capacity depends on EOL LIB supply, minimum collection quantity (based on government policies for EOL LIB collection) (Wasesa et al., 2022; Kamath et al., 2023; Albertsen et al., 2021) and time taken to increase capacity. As the EOL LIB supply from EOL EV, SES, LIB replacement, and repurposed EOL LIB increases with time, the EOL LIB supply may exceed the collection capacity (depending on the minimum collection ratio), which increases the EOL LIB landfills. The government increases the quota for minimum collection ratio to reduce the landfill, leading to increases in EOL LIB collection. An increase in the collection rate and a high fraction of EOL LIB allocated to recycling increases the recovery of raw materials and the recycling profitability. High profitability increases the fraction of EOL LIB allocation to the recycling process, which increases the difference between EOL LIB supply and recycling capacity. Recycling capacity increment depends on the difference between recyclable LIB supply and recycling capacity and the time taken to increment the recycling supply. Hence, an increment in difference leads to an increment in recycling capacity, further increasing the raw material recovery.

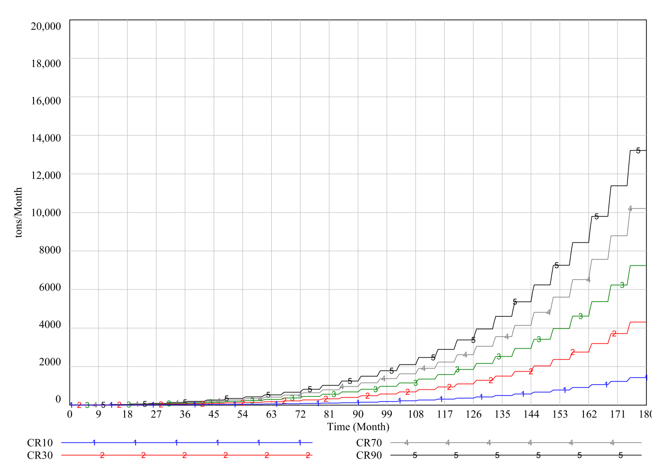
In the given scenario, “CR10- CR90” denotes the different minimum collection ratio value. Fig. 5(a) shows the recovery of Li, Fig. 5(b) shows the recovery of Ni, and Fig. 5(c) shows the recovery of Co for different minimum collection rate values. Steep changes in the recovery of raw materials signify the time taken to review collection capacity discrepancy between collection capacity, minimum collection quantity, and time to increment collection capacity and time taken to review recycling capacity discrepancy between recyclable EOL LIB supply, recycling capacity, and time to increment recycling capacity. Li, Ni, and Co recovery is high in a high recovery scenario “CR90”. In the CR90 scenario, recovery of Li reduces 16% of demand, whereas Ni and Co reduce demand by 17% of total raw materials for EV and SES. Li, Ni, and Co recovery is two times higher in the CR90 scenario compared to the CR50 scenario at the end of the simulation. In the CR10 scenario, around 2% of total raw materials for EV and SES are recovered for a given proportion of EOL LIB allocated to recycling.



(a) Li recovery

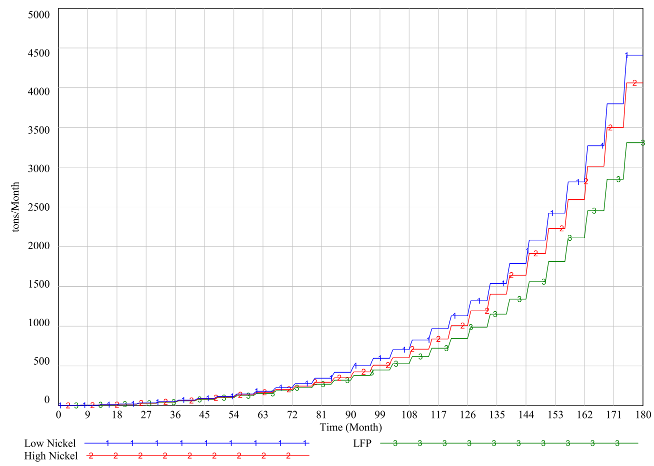


(b) Ni recovery

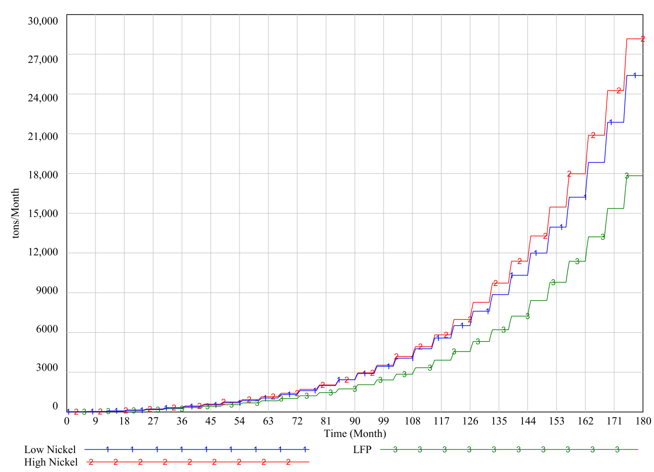


(c) Co recovery

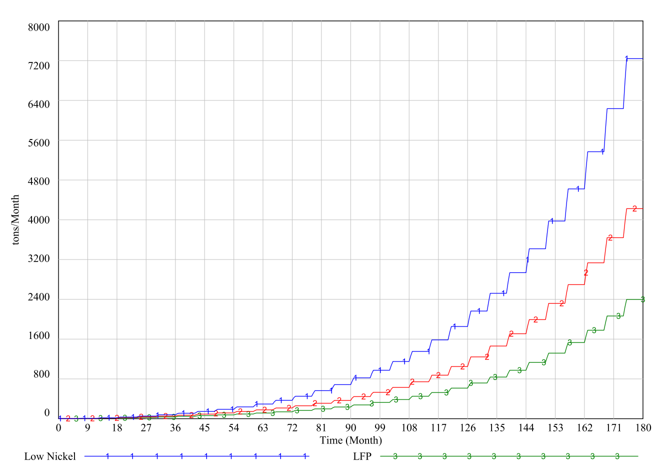
Fig. 5. Collection capacity variation impact on raw material recovery from EOL LIB.



(a) Li recovery



(b) Ni recovery



(c) Co recovery

Fig. 6. Impact of different variant compositions in collected EOL LIB on raw material recovery.

4.3. Scenario 2: Variation in LIB variant composition in collected EOL LIB

EOL LIBs stock contains different LIB variants that differ from each other based on electrodes raw material composition (Nitta et al., 2015; Pillot, 2019; Vaalma et al., 2018; Bibra et al., 2021; Liu et al., 2023). Differences in the share of LIB variants in EOL LIB (Refer to Section 3.3, Table 4), raw material composition of LIB variants (Refer to Section 3.3, Table 5), allocation of EOL LIB to recycling, availability of infrastructure for EOL LIB collection and EOL LIB handing impact the raw material recovery (Refer to Section 3.3). Variability in raw material composition in LIB electrode and different LIB variant demand influences the raw material recovery from EOL LIB as raw material recovery depends on both.

In this scenario, we analyze the impact of varying proportions of LIB variants in collected EOL LIB battery mix on raw material recovery. Figs. 6(a), 6(b), and 6(c) show variation in Li, Ni, and Co recovery with variation in LIB variants proportion in collected EOL LIB, respectively. Steep changes in the recovery of raw materials signify the increment in the difference between EOL LIB supply and collection capacity and recyclable LIB supply and recycling capacity similar to Scenario 4.3. Fig. 6(b) shows that Ni recovery is high in high Nickel scenarios as NMC811 LIB demand dominates the LIB demand. Figs. 6(c) and 6(a) show that Co and Li demand (respectively) is high in high cobalt scenarios, as NMC622 LIB dominates the overall LIB demand. Recovery of raw materials reduces the demand for total raw materials for EV and SES by 7%–10% based on differences in LIB variants composition in overall LIB demand (as defined in Table 4). Li demand is reduced by 5%–9%, Ni demand is reduced by 6%–11%, and the Co demand by 5%–10% based on the difference in LIB variants proportion in battery mix, recycling efficiency, and proportion of EOL LIB allocated to recycling. Co recovery is three times, and Ni recovery is around 1.5 times higher in high cobalt scenarios compared to LFP scenarios as LFP does not contain Ni and Co.

4.4. Scenario 3: Variation in the repurposing on second use LIB

Repurposing EOL LIB creates a secondary supply, reducing the demand for new LIB for energy storage. The availability of repurposed LIB variants (depends on different scenarios defined in Table 4) relies on the quantity of EOL LIB allocated for the repurposing and repurposing infrastructure. In this scenario, EOL LIB allocated for the repurposing process varies from 10%–90%. "RR1-RR9" where RR1 denotes the 10% of the total collected EOL LIBs allotted to the repurposing process, and RR9 denotes the 90% of the total collected EOL LIBs allotted to the repurposing process. In this scenario, "RR1, RR3, RR5, RR7, and RR9" are taken into consideration. A large quantity of EOL LIB allocation to repurposing increases the availability of LIB to be repurposed for stationary storage applications, limited by the available capacity for the repurposing process.

Fig. 7 shows the variations in the quantity of NMC811 battery obtained by repurposing the EOL LIBs. Repurposed LIB quantity increases with the increase in the EOL LIB collection, the allocation of a large share of EOL LIB (RR9) to repurposing, and adequate repurposing infrastructure. In the RR9 scenario, the LIB available for second use is around three times higher than the total repurposed LIB available in the RR3 scenario. In RR9, the availability of repurposed NMC622 is 2.7 times, and NMC822 and NCA are 2.9 times higher than the respective repurposed LIB variable available for the RR3 scenario. Recyclable NMC622, NMC811, and NCA increased by 0.2M units, 0.03M units, and 0.027M units due to the EOL repurposed LIB supply in 2030. An increment in recyclable depends on the battery mix of EOL LIB.

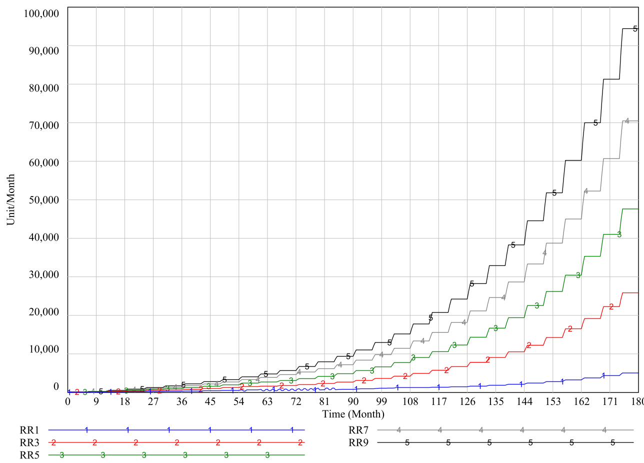
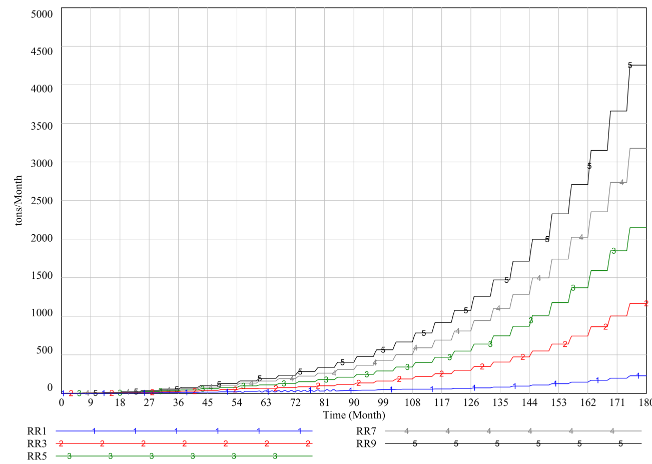
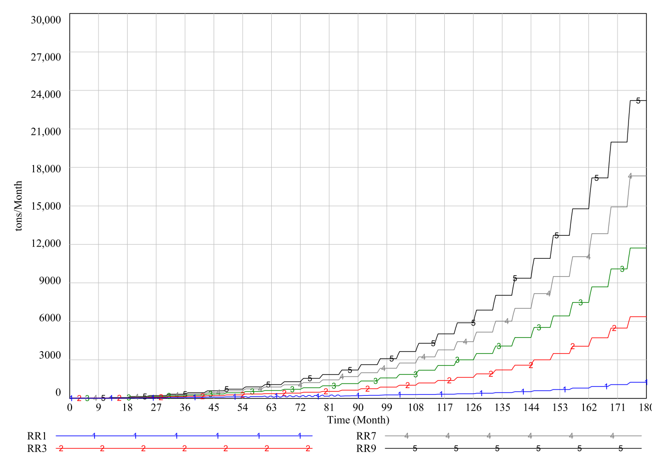


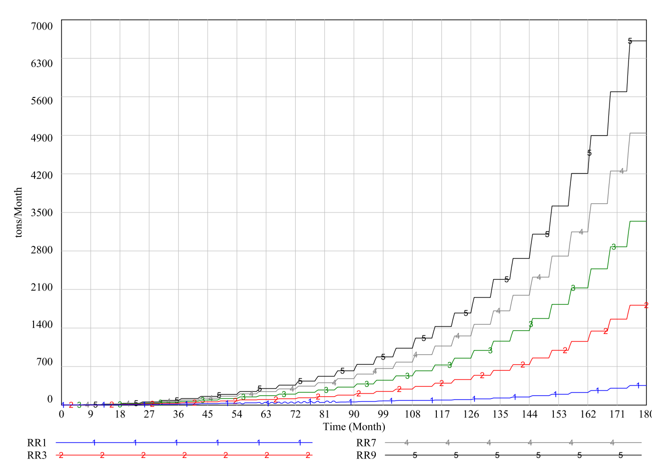
Fig. 7. Variation in the quantity of LIB available for secondary application.



(a) Li recovery



(b) Ni recovery



(c) Co recovery

Fig. 8. Repurposing impact on raw material recovery from EOL LIB.

4.5. Scenario 4: Variation in the repurposing on raw material recovery

Repurposing of EOL LIB reduces the demand for new LIB for energy storage by supplying repurposed LIB similar to Scenario 3 (Section 4.4). More repurposed EOL LIB leads to a large reduction of new LIB demand for energy storage. However, repurposing delayed the recovery of raw materials from EOL LIB as it extended the LIB life. Hence, the higher allocation of EOL LIB to repurposing reduces the quantity of recovered raw materials as more repurposing reduces the LIB allocated for recycling.

In this scenario, RR1 signifies that 10% of collected EOL LIB is allocated to repurposing facilities, whereas RR9 denotes 90% of collected EOL LIB is allocated to repurposing. Similar to Scenario 4.4, we take “RR1, RR3, RR5, RR7, and RR9” into consideration. Figs. 8(a), 8(b), and 8(c) show the variations in Li, Ni, and Co recovery, respectively, with the variation of allocation of EOL LIB to repurposing. Increment in allocation to EOL LIB to repurposing facilities leads to lower recovery of raw materials as shown in Figure 8(a)–8(c). RR9 leads to 3%–4% recovery of Ni, Co, and Ni of total Li, Co, and Ni demand from EV and SES, whereas RR1 leads to recovery of 10%–11% of total raw material demand. Focussing on the RR9 scenario, in 2035, about 3500 ton Li, 19260 ton Ni, and 5500 ton Co will be stocked in repurposed LIB.

5. Discussion

The system dynamics modeling technique is used to understand the impact of different EOL LIB handling processes on the continually increasing EOL LIB stock with different LIB variant proportions on raw material recovery. Different scenarios related to varying EOL LIB collection rates, allocation of the different LIB variants (LIB proportion in EOL LIB) to the recycling and repurposing process, EOL LIB handling process infrastructure, and delay in the development of infrastructure are assessed to analyze their impact on the raw material recovery.

5.1. Comparison with other studies’ findings

Our study mainly supports and extends the findings of other studies. Model results indicate that variation in collection rate impacts the collection of different LIB variants based on the battery mix of EOL LIB, which leads to variation in raw material recovery. Simulation results indicate that varying collection rates from 10% to 90% (CR10 to CR90) will reduce the demand for total raw materials Ni and Co by (1.8–17)%. In contrast, demand for Li is reduced by (1.7%–16%) for a different proportion of EOL LIB allocated to the recycling and repurposing process, comparable to results obtained by Xu et al. (2020), Dunn et al. (2022). The percentage of recovered material is less compared to results obtained by Liu et al. (2023) due to differences in assumptions of the model (for EOL LIB calculation (Liu et al., 2023) considers EV, consumer electronics, uninterruptible power supply, and energy storage system). Recycling will provide the recycled material when LIB reaches EOL, whereas repurposing delays the material recovery as repurposed LIB is used for secondary application (Fig. 2). Recyclable LIB variant supply is reduced by 0.027M–0.2M (based on the high cobalt scenario defined in Table 4) when EOL LIBs are allocated to repurposing as repurposing delayed the LIB to recycling based on LIB warranty life for repurposed application. Due to repurposing (RR3 Scenario), LIB addresses to recycling in 2035 are estimated to be 1.4 times lower than those of Scenario when all the EOL LIB allocated to recycling. Reduction in recyclable quantity is slightly higher than Bobba et al. (2019) (LIB address to recycling in 2035 are estimated to be 1.25 times lower) because Bobba et al. (2019) consider a gradual increase in repurposing till 20%. In contrast, we considered 30% of EOL LIB allocated to repurposing.

Along with collection capacity and the trade-off between recycling and repurposing, the availability of different LIB variants in EOL LIB also impacts the recovery of raw materials from EOL LIB, affecting raw material demand. Variation in LIB variants demand defined in the High Nickel scenario in Table 4 leads to 41% lower recovery of Co compared to high cobalt scenarios. In contrast, material recovery of Li, Ni, and Co is low for the LFP scenario compared to other scenarios in Table 4 due to the difference in the proportion of constituent's raw materials in LIB variants contained in EOL LIB stock (Xu et al., 2020; Dunn et al., 2022; Kamath et al., 2023).

5.2. Theoretical contributions

This study provides a model to analyze the tradeoffs between different circular economy (CE) strategies used for raw material recovery from EOL LIBs that contain different LIB variants (variants differ in raw material compositions of electrodes). Most of the literature assumes that LIB replacement that impacts EOL LIB stock depends on the LIB warranty life and excludes the impact of charging frequency on LIB replacement (Shafique et al., 2022; Huster et al., 2024). Our analyses overcome this assumption by highlighting that LIB replacement depends on LIB warranty life and charging frequency. EOL LIBs are collected from different vehicles to adhere to government policy regarding collection rates to reduce landfills. Our model results highlight that EOL LIB collection infrastructure and battery mix in EOL LIB impact the collection of different LIB variants that will affect the raw material recovery from EOL LIB in the future based on adopting different CE strategies like recycling and repurposing. Repurposing enhances the longevity of EOL LIB by extending LIB utilization in applications like energy storage, peak shaving, back-up, frequency regulation, and renewables integration (Chen et al., 2019). It adds to the recyclable LIB supply stock when it reaches their EOL.

EOL LIB stock segregation for recycling and repurposing depends on the profitability of both processes. Many frameworks highlight that recycling profitability depends on the recyclable quantity, which depends on recycling capacity, recycling process efficiency, battery capacity, recovery of raw material, and raw materials cost. In contrast, repurposing profitability depends on the repurposed quantity that depends on repurposing capacity, battery capacity, and cost of repurposed battery per kWh. Our model results highlight that along with capacity, time delay and incremental change in capacity impact the profitability of the EOL LIB handling process, which influences the EOL LIB allocation to recycling and repurposing and, hence, raw material recovery.

5.3. Policy implications

Previous studies have shown that multiple stakeholders interact to ensure the proper handling of EOL LIB (Glöser-Chahoud et al., 2021; Yang et al., 2024). This study proposes an SD modeling approach that provides a conceptual framework to analyze the impact of interaction among multiple stakeholders involved with different CE strategies that enable raw material recovery. Hence, this framework will help policymakers contextualize the impact of tradeoffs between different CE strategies on raw material recovery from EOL LIB. Raw material recovery from EOL LIB depends on LIB variant proportion in EOL LIB stock, the chemical composition of LIB variant's electrodes, and collection rate (Liu et al., 2023; Shafique et al., 2023). Our model simulation results highlight that the battery mix composition of EOL LIB combined with high collection leads to high raw material recovery. Therefore, battery manufacturers' choice of LIB variants and policies supporting improvement in the collection facility infrastructure improves material recovery, reducing recycling and repurposing costs per kWh. LIB variants such as LFP yield lesser recovery, so they can be routed to repurposing and energy storage. This will put forward the need for a proper policy framework that enables separate collection and sorting of LIBs for different variants.

Apart from LIB variant mix and collection capacity infrastructure, tradeoffs between CE strategies like recycling and repurposing, the efficiency of the handling process, and recycling and repurposing infrastructure will also impact raw materials recovery. Hence, countries like India with scarce sources of strategic raw materials (like Li, Ni, and Co) and in the nascent stage of LIB manufacturing should frame policies focused on incentivizing better collection and EOL LIB handling techniques to alleviate the raw material recovery and availability of repurposed LIB for SESs to reduce the import dependency on raw material and LIB.

5.4. Limitations

Although the findings regarding the examined variables align with the existing literature, the variables are limited to the collection rate, consumer preferences for LIB variants, and allocation of EOL LIB for recycling and repurposing. In this study, we consider only the impact of the market share of NMC, NCA, and LFP in EOL LIB stock on raw material recovery. Battery technologies are undergoing revolutionary breakthroughs to develop LIBs like lithium-air, lithium-sulfur, sodium-ion, and solid-state batteries (Zeng et al., 2022; Ren et al., 2023). Adopting these LIB chemistries in the future will impact the raw material recovery and second use of EOL LIB. Therefore, future investigation is required to explore the impact of market share on the EOL LIB handling process for future LIB chemistries.

This study employs SD modeling to understand the impact of tradeoffs between the EOL LIB handling process and raw material recovery. However, this study needs to account for the effects of changes in policy framework on EOL LIB handling infrastructure development. Additionally, the EOL LIB handling process has environmental (Richa et al., 2017; Kamath et al., 2020) and economic impact (Xiong et al., 2020; Schulz-Mönninghoff and Evans, 2023) based on the quality assessment of the EOL LIB. Changes in the regulatory framework either support or hinder the infrastructure development that will impact the environmental and economic feasibility of the EOL LIB handling process, thereby affecting the recovery of raw materials.

6. Conclusions

This study utilizes system dynamics modeling to understand the variability in raw material recovery based on scenarios on EOL collection rates, LIB variants, and repurposing rates. Based on the analysis, we conclude that EOL LIB collection infrastructure improvement and regulation framework on EOL LIB collection reduces the landfill by enabling better EOL LIB collection, consumer preferences for material-rich LIB variants may prove beneficial with higher recovery rates compared to others, and the EOL LIB stock exhibits an upward trend with increasing demand for LIB in EVs and energy storage, with repurposed LIB partially fulfilling the LIB demand for energy storage. Continual improvement of the EOL LIB handling process, collection infrastructure, and selection of proper CE strategies plays a crucial role in the future security of LIB raw material demand. Recycling improves the raw material supply by recovering raw material from EOL LIB, whereas repurposing enhances LIB longevity as repurposed LIB is used to meet the SES demand. The LIB variant proportion in EOL LIB and their electrods' composition also impact raw material recovery. Thus, original equipment manufacturers (OEMs) involved in the EOL LIB handling business should plan their strategies by considering the demand for material-intensive LIB.

This study considers LIB's demand for electric cars and SES. The model can be enhanced by considering EV variants like electric buses, two/three-wheelers, and electric trucks. This research considered only NMC, NCA, and LFP LIB chemistries for analysis. Therefore, this research can be extended to cover the impact of future batteries on the recovery process. Along with different LIB variants, collection facilities, recycling, and repurposing infrastructure also impact material recovery. Improvement in infrastructure needs investment and transparent government policies. This study can be extended by including the social factors and policy differences between developed and emerging economies' impact on the CE strategies used for handling EOL LIB. The recent Conference of Parties (COP27) and policies adopted by countries like the U.S. and different parts of Europe for stringent emission standards have refocused the global effort on developing sustainable technologies for clean mobility, carbon neutrality, etc. The model boundary can be extended by adding the impact of policy aspects such as government emission targets, manufacturers, and government future EV sales target commitment to establishing the circular economy for handling EOL LIBs.

CRediT authorship contribution statement

Bhanu Pratap: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **T.V. Krishna Mohan:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **R.K. Amit:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Shankar Venugopal:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.spc.2024.07.027.

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