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Managing automotive end-of-life NiMH and Li-ion batteries in Mongolia: a Material Flow Analysis to assess challenges and opportunities for circular batteries in the Global South

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Introduction: Mongolia's transition to electric mobility presents environmental opportunities to mitigate air pollution and potentially reduce greenhouse gas emissions but also generates complex waste streams such as end-of-life (EoL) Nickel Metal Hydride (NiMH) and Lithium-Ion Batteries (LIB). This study investigates the status of Mongolia's waste management system and how it can be optimized to enhance the circularity of such waste streams.

Methods: Original data was collected through field research at collection, repair, storage, and disposal sites, and complemented by stakeholder interviews and an analysis of the country's waste management legislation. Official vehicle fleet statistics (2010–2023) were used to forecast the quantity of EoL NiMH and LIB until 2050 and conduct a Material Flow Analysis for 10 different scenarios. The dataset comprises both qualitative data, describing the current waste management scenario, and quantitative data on vehicle imports, fleet composition, and battery specifications, with assumptions for missing values based on market trends.

Results: Results reveal that Mongolia lacks infrastructure and policy for safe and sustainable EoL battery management. EoL battery outflows were estimated using a two-parameter Weibull distribution model; forecast reliability was assessed via out-of-sample backcasting of the vehicle-fleet projection against historical fleet statistics (2019–2023 hold-out: MAPE = 4.71%). The results of the EoL battery quantities are scenario- and parameter-dependent projections for the lifetime and battery-specification assumptions. The results show that cumulatively (from 2023 to 2050), in the Current Scenario, 10,302 tons of EoL NiMH and 38,650 tons of EoL LIB are expected to be generated. In contrast, for the Climate Focus Scenario, 10,455 tons of EoL NiMH and 102,586 tons of EoL LIB are expected.

Discussion: The lower values of NiMH in 2050 are due to the expected transition from NiMH to LIB in HEV. Recommendations to enhance EoL battery management's circularity include focusing on improving EoL battery collection, implementing Extended Producer Responsibility, integrating the existing informal sector, enhancing regional and international cooperation, and improving data acquisition and management. In summary, a combined approach involving local and international cooperation and socio- and technological development is essential for improving the circularity of EoL battery management in Mongolia.

KEYWORDS

circular economy, end-of-life batteries, global south, lithium-ion battery, material flow analysis, Mongolia, NiMH battery, waste management

1 Introduction

In Mongolia, a country with nomadic traditions reaching back at least two millennia, mobility was based on horses and camels throughout most of the country's history (Miller, 2024; Taylor et al., 2021), causing only minimal impacts on the environment. In the context of urbanization and globalization, particularly in the post-socialist period since the 1990s, private vehicle ownership in Mongolia has increased and contributed not only to traffic congestion but also to massive urban air pollution (Karthé et al., 2022; Ganbat et al., 2022). According to the Ministry of Road and Transport, there has been an increase from 841,552 vehicles on the road in 2016 to 1,264,892 vehicles in 2022 (MRT, 2022), mainly in the capital city of Ulaanbaatar, where the current number of passenger vehicles has exceeded 500,000 since 2022 (NSO, 2025a). When looking into the type of vehicles with the highest growth rate in the country, Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) are at the top of the list with an increase of 37.5 and 13.5% respectively, from 2021 to 2022 (MRT, 2022). BEVs are fully electric vehicles powered solely by rechargeable batteries, while HEVs combine an internal combustion engine with an electric motor and battery, which is charged through regenerative braking and engine power. Both are types of Electric Vehicles (EVs), a broader category that includes any vehicle using electric propulsion. A notable feature of Mongolia's vehicle market is the dominance of imported used vehicles, particularly the Toyota Prius, which accounted for 21.4% of all passenger cars in 2022 (MRT, 2022). More recently, sales of BEVs have been increasing, driven by the arrival of several Chinese manufacturers on the Mongolian market. This increase in the adoption of HEVs and BEVs is driven not only by the perspective of lower operational costs, but also by the environmental benefits they bring, such as lower greenhouse gas emissions and overall local air quality improvement (Pamidimukkala et al., 2024). To support this transition, many countries, including Mongolia, have been implementing financial incentives to facilitate and increase the adoption of EVs (UNEP, 2021; Mendjargal et al., 2022). One of Mongolia's EVs promotion strategies has been to exempt excise taxes to support the import of used hybrid and electric vehicles (UNEP, 2020). Considering that Mongolia does not have a strongly developed national automobile manufacturing business, this has accelerated the quantity of imported used HEV and BEV from Japan, which is Mongolia's primary source of vehicles (Wang and Okubo, 2019). A report by UNEP (2020) shows that the import of used hybrid vehicles from Japan to Mongolia tripled from 2012 to 2016. The import and total number of BEV and HEV are expected to continue growing (Mendjargal et al., 2022). However, besides the beneficial environmental aspects of the transition to e-mobility, the challenges of handling these vehicles at their end-of-life must be considered (Prates et al., 2023). Most HEVs, such as the Toyota Prius, use Nickel-Metal Hydride (NiMH) batteries in older-generation vehicles and Lithium-Ion Batteries (LIB) in their newer models (Guo et al., 2023). LIBs have numerous advantages, such as higher energy density, making them ideal for increasing storage capacity while minimizing battery size and weight. They offer longer driving range, faster

charging than older technologies like NiMH, and require lower maintenance (Mossali et al., 2020; Kotak et al., 2021). NiMH batteries have higher durability and lifetime cycles but lower power and energy density (Safdar et al., 2017). While NiMH batteries tend to be safer than LIBs (in terms of thermal stability and fire risks), NiMH batteries also harm the environment when discarded improperly (Liu et al., 2019). Therefore, both HEVs and BEVs' batteries require a much more complex management system at their end-of-life (EoL) than the starter batteries used in cars with internal combustion engines (Kotak et al., 2021). If the batteries are not properly recycled and disposed of, soil, water and other environmental resources will be polluted, which may counteract the benefits of HEVs and BEVs regarding climate protection and air pollution prevention. Ultimately, under a Resource Nexus perspective (Brouwer et al., 2024; Prates et al., 2025), this would question the positive overall assessment of electric mobility.

Until today, Mongolia lacks the capacity to treat, recycle, and dispose of end-of-life HEVs, BEVs, and their batteries (Mendjargal et al., 2022). Considering that the increased adoption of BEVs and HEVs in the country will inevitably lead to growth in EoL LIBs and NiMH batteries, it is necessary to find an optimal solution to handle this type of waste stream in Mongolia and guarantee environmental and human health protection.

Despite the increasing relevance of this issue, scholarly attention to EoL battery management in Mongolia remains limited. Existing studies have estimated battery volumes (Wang and Okubo, 2019), vehicle lifespans (Mendjargal et al., 2022), and provided situational assessments (GIZ, 2022). However, these works do not sufficiently assess the current status of waste management capacities nor address the pathways to transition toward a circular economy or the transnational dynamics of reverse logistics. The existing studies have not integrated EoL battery forecasting with explicit mass-balanced representations of EoL management pathways; as a result, future waste generation and recovery potentials are not consistently quantified in a way that supports long-term infrastructure planning. Therefore, the research gap persists, lacking a comprehensive evidence-based, forward-looking basis to design EoL battery governance and infrastructure proportional to expected volumes and aligned with circular economy objectives.

This study addresses these limitations by explicitly combining a forecasting model with a scenario-based, mass-balanced system representation. Specifically, the paper combines a two-parameter Weibull distribution for forecasting EoL battery outflows with a Material Flow Analysis (MFA) framework to quantify and compare EoL management pathways under alternative assumptions. The Weibull approach supports a probabilistic representation of battery retirement, and the MFA provides a transparent mass-balance framework that enables consistent allocation of forecasted EoL quantities across collection, reuse, recycling, and disposal routes under explicit scenarios. By integrating these tools, the study moves beyond describing the problem to quantifying the extent to which different pathway configurations could close capacity gaps and reduce environmental risks. Accordingly, this paper addresses the following overarching

research question: How can the waste management systems in Mongolia be optimized to support a successful transition to a circular economy?

To address the research question, the study followed a four-step methodological approach: (1) assessment of Mongolia's legal framework and current waste management infrastructure for end-of-life NiMH and LIB batteries through field research and stakeholder interviews; (2) forecasting of EoL battery volumes until 2050 using a two-parameter Weibull distribution; (3) development of scenario-based EoL battery management pathways for 2050, varying collection, reuse, recycling, and disposal rates; and (4) construction of Material Flow Analysis to support evidence-based decision-making for sustainable battery waste management and circular economy transition.

The study contributes novel insights into how circular economy strategies can be adapted to low-volume, complex waste streams in countries with underdeveloped infrastructure. More specifically, this work adds to literature by providing an integrated forecasting-mass balance approach which can support long-term waste management planning. Additionally, considering Mongolia's reliance on second-hand imports from Japan, it presents a key case for analyzing international reverse logistics and transboundary resource governance (Yamaguchi, 2021). Therefore, this work also advances the discussion of waste governance strategies in an international context.

The remainder of the paper is structured as follows: Section 2 presents a literature review of the key strategies to manage EoL batteries. Materials and methods used for the research are described in Section 3. The remainder of this research paper is structured as follows: Section 4 brings key results, including an overview of mobility development in Mongolia, the current waste management situation in Mongolia, and the results of the scenario-building process. Section 5 discusses the results, and Section 6 brings the concluding remarks and key policy recommendations.

2 State of the art: the circularity challenge of end-of-life electric vehicle batteries

The traction batteries used in hybrid and fully electric vehicles are among the largest and most numerous, accounting for an increasingly significant share of total battery waste flows. Considering that current battery chemistries pose potential environmental and human health hazards and rely on limited raw materials, circular material use is essential for their overall sustainability. However, as EV batteries constitute a relatively novel waste stream, capacities for recycling and disposal are still limited in many parts of the world. It is important to understand how waste flows develop in terms of volumes and composition to guide future policies for the sustainable management of EoL EV batteries.

2.1 End-of-life battery management

Following the circular economy principles, this section reviews the key characteristics and alternatives to manage EoL LIB and NiMH batteries.

2.1.1 Characterization

2.1.1.1 NiMH

NiMH batteries have been used in HEV since the early 1980s by different vehicle makers, such as Toyota, Honda, Ford and Chevrolet (Korkmaz et al., 2018). Even though LIBs have lately been dominating the battery market, it is estimated that NiMH batteries still hold a market value of 4.5 billion USD in 2025 (Inkwood Research, 2022), and a substantial number of NiMH batteries are either inoperable, experiencing performance degradation, or approaching the end of their service life (Martínez-Sánchez et al., 2024).

As an example, a NiMH battery from a Toyota Prius (Generation 2) consists of 28 battery modules, each containing six 1.2 V cells, and each module weighs 1.04 kg; with the additional parts such as the battery fan and battery case, the total weight is around 39.07 kg (Wang et al., 2021a). Regarding its elemental composition, until today, academics have been trying to determine NiMH batteries' content accurately. As Rodrigo et al. (2025) discussed, variations in values found in academic literature result from methodological choices, including whether to account for the cathode elements, anode elements or both jointly. The overall NiMH battery composition by weight adopted by Iloeje et al. (2022) is presented in Table 1.

As can be seen, end-of-life NiMH batteries contain critical raw materials such as rare earth elements (REEs) – Lanthanum (La), Cerium (Ce), Praseodymium (Pr), and Neodymium (Nd). These batteries are the second-largest alternative source of REE (after magnets) and are currently underused since recycling rates are still below 1% (Rodrigo et al., 2025). In the case of the Toyota Prius HEV, overall, they can contain from 10 to 15 kg of rare earth metals (Rodrigo et al., 2025).

2.1.1.2 LIB

Similar to NiMH batteries, LIBs were initially introduced in portable electric and electronic devices, and have gradually become

TABLE 1 NiMH battery composition.

Material	Content in NMC batteries (w %)
Ni	30.60%
Fe	7.40%
La	4.90%
Ce	1.30%
Pr	0.30%
Nd	0.80%
Co	2.50%
Mn	2.50%
Al	1.00%
KOH	3.40%
H ₂ O	10.30%
Leveling Agents	1.00%
Plastic (PP)	4.90%
Ni(OH) ₂	12.10%
Pack	17.00%

Source: Iloeje et al. (2022).

the leading rechargeable battery technology, including for electric vehicles (Zhang et al., 2023). Today, BEVs account for the highest share of LIB consumption, consisting of up to 90% of the total final usage (Rezaei et al., 2025). It is relevant to state that the designation “LIB” covers a wide range of different battery chemistries. LIBs are mainly defined by the type of cathode materials used, being classified into the following main groups: lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), and lithium nickel manganese cobalt oxide (NMC), with NMC and LFP having a higher market share (Hantanasirisakul and Sawangphruk, 2023). Nevertheless, LIB can have different chemistries and shapes (cylindrical, prismatic or pouch cells), enhancing the difficulty of standardizing and scaling its refurbishment, reuse and recycling processes (Harper et al., 2019). The estimated composition of a LIB with NMC chemistry is presented in Table 2.

Among the presented elements, lithium (Li), cobalt (Co), and nickel (Ni) have high economic value (Rezaei et al., 2025). The value of these metals is subject to high variations due to geopolitical, social and economic situations (Hantanasirisakul and Sawangphruk, 2023). This leads to increasing efforts to reduce the critical material content (such as cobalt), which supports reducing and stabilizing battery costs (Rezaei et al., 2025). Moreover, numerous battery technology developments (e.g., solid state, sodium-ion, lithium-air batteries) are underway to improve cost, energy density, lifecycle and other technical aspects (Miao et al., 2022). As stated by Zanoletti et al. (2024), design for recycling – a key step in CE – must include using recyclable materials, easy disassembly and facilitated material recovery.

After finishing their first useful life both NiMH and LIB should be assessed and classified to decide which is the most suitable path for further management (Yu et al., 2017). A relevant initiative to facilitate this assessment by allowing better identification of the battery characteristics is the Battery Digital Passport, a concept being introduced by the European Union, which will not only support enhancing reuse and recyclability but also allow better traceability and

compliance of end-of-life battery management (Rufino Júnior et al., 2024).

NiMH and LIB batteries are generally classified as hazardous waste. In the case of LIB, according to the UN 3480/UN 3481, it is classified as a Class 9 hazardous material. This classification leads to specific requirements for collection, transportation and storage. Caution during this process is even more necessary when handling EoL LIB, since they are more prone to thermal runaways and can lead to fire outbursts (Tran et al., 2022). While LIBs are not explicitly listed in the annexes to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (SBC, 2023), a working group at the Secretariat of the Basel Convention has pointed out the need to create national inventories of waste LIBs and regulate their trade (Kendall et al., 2023).

2.1.2 Repair and reuse

2.1.2.1 NiMH

When large batteries start to malfunction, it is common that they are taken to repair shops where they are disassembled, tested, the low-capacity modules are swapped, reinserted, the battery pack is rebalanced and retested, and ultimately, sent back to its owner (Simons et al., 2022). As an alternative, when the battery capacity lowers, end-of-life NiMH batteries can potentially be repurposed and reused to complement solar energy systems to provide off-grid power in communities that do not have access to reliable electricity (GIZ, 2022). A basic PV system will consist of a solar panel, battery, charge controller, and lights (Simons et al., 2022). The battery is the costliest part of these systems, reaching up to 29% of the total cost. Therefore, as shown by Simons et al. (2022), using repurposed NiMH batteries, compared to new lead-acid batteries, is more environmentally friendly and reduces the total initial and replacement costs. Nevertheless, the author also highlights that to guarantee adequate system operation, an appropriate solar charge controller must be developed (Simons et al., 2022).

2.1.2.2 LIB

Equally, after retiring from an electric vehicle, a few choices are available for the spent LIBs depending on their state-of-health (SOH) and remaining useful life (RUL) (Etxandi-Santolaya et al., 2023). For the LIB packs that are still functioning with 70–80% of their initial capacity, they can be repurposed and reused in less demanding applications (Amusa et al., 2024). Battery second use is considered a promising option from an economic and environmental perspective (Kotak et al., 2021). The use of retired EV batteries as energy storage systems, when compared to new batteries, can reduce the electricity cost and carbon emissions by 12–57% and 7–31%, respectively (Amusa et al., 2024). Therefore, using retired vehicle batteries in other applications leads to several environmental benefits (e.g., less extraction of raw materials, lower energy consumption and less GHG).

Nevertheless, as with NiMH, accurate assessment of the battery condition is fundamental to ensure that reuse is a safe option. It is relevant to say that EoL battery repurposing (be it NiMH or LIB) is not trivial and should be conducted by trained workers to avoid harming human health and the environment (GIZ, 2022). In addition, reusing EV batteries extends their lifespan and provides time to improve recycling capacity and technology (Hantanasirisakul and Sawangphruk, 2023).

TABLE 2 LIB (NMC) battery composition.

Material	Content in NMC batteries (w%)
Al	22.72%
Co	8.45%
Cu	16.60%
Fe/Steel	8.79%
Lithium	1.28%
Mn	5.86%
Ni	14.84%
Binder	1.39%
Carbon (non-graphite)	3.47%
Electrolyte + solvent	1.66%
Fluoride	4.99%
Oxygen	4.52%
Phosphorus	2.04%
Plastics	3.29%

Source: Winslow et al. (2018).

2.1.3 Recycling

After their second life, batteries must be recycled to allow the recovery of their content. The first step of this process includes a pre-treatment that can be done manually or mechanically and generally consists of battery disassembly (Miao et al., 2022). It should be guaranteed that the battery is fully discharged/deactivated, and afterwards, the battery goes through crushing, sieving, magnetic and gravity separation (Chabanet, 2019). The mechanical pre-treatment process has the advantage of being faster, cheaper and more scalable. Nevertheless, it lowers the recovery efficiency since it mixes all components. On the other hand, even though manual pre-treatment improves material recovery, it increases costs due to the required skilled workforce and higher time demand (Miao et al., 2022). Automation is still a challenge due to the multiple designs of battery packs (Hantanasirisakul and Sawangphruk, 2023). The pre-treatment generates what is known as black mass powder, which can follow pyrometallurgical and/or hydrometallurgical operations to recover its contents (Bhar et al., 2023).

Pyrometallurgical recycling processes involve extracting metals or metal compounds using high temperatures (He et al., 2024). Even though pyrometallurgy can be considered a more straightforward method, which can handle higher volumes of end-of-life batteries, it generally has a higher carbon footprint and lower purity of products when compared to hydrometallurgical processes (Korkmaz et al., 2024).

The hydrometallurgical process starts with the dissolution (leaching) of the black mass, followed by metal purification (Rinne et al., 2024). The chemistry of the process varies depending on the composition of the battery and the leaching agents used (e.g., inorganic acid, ammonia or organic acid leaching; Wu et al., 2024). After leaching, metals and metal compounds are separated from the leachate and purified (Wu et al., 2024). Hydrometallurgy holds several advantages, including its ability to recover almost all the components of the spent NiMH and LIBs with higher purity and less energy-intensive than pyrometallurgy (Wu et al., 2024). Nevertheless, the method still presents several environmental drawbacks, such as the use of highly toxic chemicals, significant water demand, and production of hazardous waste (Korkmaz et al., 2024).

Direct recycling is also an alternative recycling route. This process consists of repairing the crystal structure of the battery electrode, and it is suitable for batteries that have not been heavily damaged, and for which the electrode composition is known (Hantanasirisakul and Sawangphruk, 2023). Even though this process has advantages (e.g., less complicated process, lower environmental impact when compared to pyro- and hydrometallurgy; better output), it also faces the drawbacks of requiring exact information of the battery chemistry and demanding sorting processes, which are challenging to scale up (Hantanasirisakul and Sawangphruk, 2023). As can be seen, EoL NiMH and LIBs' most conventional recycling methods still face technical, environmental, and economic challenges (Korkmaz et al., 2024).

2.1.4 Disposal

NiMH and LIB are generally considered hazardous waste due to their components. Batteries containing metals like Li, Ni, Pb, Hg, Zn, Cr, and Cd become toxic for the environment and human health if they are not properly disposed of (Pradhan et al., 2022; Prates et al., 2023; Bai et al., 2024). Hence, burying or incinerating EoL batteries is

not considered appropriate, not only due to the potential release of toxic and hazardous gasses into the environment but also because it is a reliable source of scarce materials (Rezaei et al., 2025).

3 Materials and methods

3.1 Study site

Mongolia is a landlocked country which borders only Russia and China. The country has a total area of about 1,564,116 km², making it the largest landlocked country in the world (Mendjargal et al., 2022). Mongolia is classified as a lower-middle-income country, and in 2023, the human development index (HDI) was 0.741, ranked 96 out of 193 countries and territories in the world (UNDP, 2024).

Mongolia has a strong nomadic culture and has only started its urbanization process after the end of socialism in 1991 (Hamiduddin, 2023). Between 2000 and 2011, due to the flourishing mining sector, the country experienced rapid economic growth, which led to a significant increase in GDP per capita (Mendjargal et al., 2022). This economic growth resulted in a fast change in lifestyle and an increased migration of citizens toward the capital, Ulaanbaatar (UB). The country's population was estimated to be 3.454 million in 2024, and almost half of the population lives in the capital (Hamiduddin, 2023; UN, 2024).

Due to urbanization, and according to Leung and Lee (2022), the number of registered vehicles in Ulaanbaatar increased 300% in the last decade. The city's rapid population growth and heavy traffic brought severe infrastructural and environmental challenges, reducing life quality and well-being (Leung and Lee, 2022). Without an efficient public transport, the city's inhabitants strongly rely on private cars, old busses and a range of informal transport modes (Leung and Lee, 2022). In Mongolia, the number of HEV in use reached 29.9% of all state-inspected vehicles, overtaking diesel vehicles (28.9%) but still less than petrol vehicles (41.2%) (GIZ, 2022). The reason for this broad adoption is twofold: the exemption of HEVs from excise duty and air pollution controls (which significantly reduced purchase costs) and the ability of HEVs to endure the harsh winters of the country, which can reach temperatures as low as -40 °C (GIZ, 2022).

An often-cited problem of Ulaanbaatar city is the poor air quality, mainly caused by using coal-fired stoves for cooking and heating (Soyol-Erdene et al., 2021; Ariunsaikhan et al., 2023). Nevertheless, studies have shown that vehicles contribute more than 10% of the city's total pollution volume (Agvaantseren et al., 2022). Therefore, air pollution control is one of the key drivers for the government to promote the adoption of low-emission vehicles. However, as Mongolia's energy mix is mostly coal-based, the environmental benefits of battery electric vehicles are limited until the decarbonization of the electricity sector significantly advances (Zegas and Zegas, 2018).

The number of passenger vehicles is expected to continue to rise (Soyol-Erdene et al., 2021). Therefore, another challenge to be faced by the Mongolian government is how to handle end-of-life vehicles properly (Yu et al., 2017; Wang and Okubo, 2019; GIZ, 2022; Mendjargal et al., 2022).

3.2 Method

Material Flow Analysis (MFA) is a consolidated tool to understand a given material's mass flows and stocks within a specific system

(Chang et al., 2009). It has been widely used to map opportunities for improving material and waste management efficiency, identify material recovery potentials, and has highly relevant results for guiding public policy development (Allesch and Brunner, 2015; Cliff and Druckman, 2015; Shafique et al., 2022). In practice, when applied to waste management systems, MFA involves collecting data on material inflows (quantities entering the system), tracking how these materials are transformed (through reuse, refurbishment, or recycling), accumulated within the system (stocks), and identifying the type and quantity of materials leaving as outflows (Allesch and Brunner, 2015).

A combination of methods was used to forecast the development of end-of-life battery generation in Mongolia and construct the MFA. The first step was to forecast the evolution of the total vehicle fleet using the approach described and validated by Duarte Castro et al. (2021), which consisted of calculating the vehicle per capita trend based on historical data and using it to project the future vehicle fleet, together with available population development forecasts. The number of vehicles per capita was calculated by dividing the car fleet by each year's population. The results were plotted, and the growth rate of vehicles per capita was obtained. Using the population forecast until 2050 from the United Nations, Department of Economic and Social Affairs (UNDESA, 2022) it was possible to project the number of passenger vehicles until 2050. The detailed calculations and results are shown in the Supplementary material.

The next step was to determine the yearly distribution of different types of passenger vehicles: battery electric vehicles (BEV); hybrid electric vehicles (HEV); internal combustion engines (ICE) with diesel (ICE-D), gasoline (ICE-G) and natural gas (ICE-NG) until 2050. This distribution was defined based on the publication of the International Transport Forum (ITF, 2023). The publication established decarbonization scenarios, which were validated by the Mongolian Ministry of Road and Transport and included the construction of two pathways until 2050, namely "Current Policies" and "Climate Ambition." In this work, we will rename the latter to Climate-Focus Scenario. The referenced project not only foresaw the introduction of low-carbon emission vehicles, but also the development of a more "efficient, reliable and integrated public transport network" and introduced shared and active mobility to support public transport. For this study, the final target shares for 2050—namely, 16.3% BEVs and 2.1% HEVs for the Current Policy scenario, and 49.2% BEVs and 4.6% HEVs for the Climate-Focus scenario—were directly adopted from the ITF report as anchor points for scenario development. To generate the annual distribution for each vehicle type from the present to 2050, the share of electric and hybrid vehicles was progressively increased each year to reach the ITF-defined targets in 2050. The adopted values are shown in the Supplementary Table S3.

After calculating the yearly quantity of each type of vehicle until 2050, the next step was to determine the resulting end-of-life batteries originating from HEV and BEV. A recent and comprehensive review by Rettenmeier et al. (2025), evaluating various forecasting methods for EoL batteries, explicitly determined that the two-parameter Weibull distribution (Equation 1) is not only common but also highly robust for this application, citing evidence from multiple studies in the e-waste and EoL battery forecasting field (Oguchi et al., 2006, 2008; Matsuno et al., 2012; Islam and Huda, 2019, 2020). Therefore, this study utilized the two-parameter Weibull probability density function, as strongly validated by the literature and by Rettenmeier et al. (2025),

$W(j)$ (Equation 1), to calculate the percentage of EoL batteries reaching end-of-life j years after sale. The total annual volume of EoL batteries was then calculated by aggregating these values with the corresponding sales, as defined in Equation 2.

$$W(j) = \left(\frac{k}{\lambda}\right) \times \left(\frac{j}{\lambda}\right)^{k-1} - \exp\left[-\left(\frac{j}{\lambda}\right)^k\right] \quad (1)$$

$$EoL\ Batteries(t) = \sum Sales(t-j) \times W(j) \quad (2)$$

λ is the scale parameter and is equal to the average lifetime of an EV or its battery; k is the shape parameter, which determines the change in the battery failure rate over time. The values adopted for each parameter, as presented in Table 3, were sourced from academic literature.

To calculate the number of EoL LIBs, it was assumed that the lifespan of the BEV and its battery are the same (also following the approach by Rettenmeier et al., 2025). This assumption is adopted by several authors who claim that battery lifespan is higher than expected and that, generally, batteries will not force BEV retirement (Kamran et al., 2021; Canals Casals et al., 2022; Nurdiawati and Agrawal, 2022). Additionally, the costs of a new battery are currently too high and not affordable to replace, leading to the retirement of the BEV (Nguyen-Tien et al., 2025).

Nevertheless, in the case of HEV, whose lifespan tends to last longer in Mongolia (as shown by Mendjargal et al. (2022)), batteries are expected to be replaced. To estimate the number of batteries being replaced in HEV, we calculated the difference between the expected EoL HEV and its batteries for each year. This approach is illustrated in Figure 1.

Annual vehicle sales data is not available in Mongolia's official databases. Since Mongolia has no domestic automobile manufacturing industry (Davaakhuu, 2013) all vehicles are imported. In such cases, studies have adopted the number of imported vehicles as a proxy for fleet stock development (Gorham et al., 2017). Therefore, yearly vehicle sales were estimated using vehicle import data. Historical data analysis revealed that vehicle imports represented, on average, 10% of the existing vehicle fleet each year (detailed in Supplementary Table S4). This ratio aligns with broader fleet growth trends and is corroborated by previous studies. For instance, Mendjargal et al. (2022) reported that the number of passenger vehicles in Mongolia increased over the past decade, with an average annual growth rate of 11%. Thus, this 10% ratio was applied to forecast future annual vehicle sales through 2050. The adopted annual sales values are shown in Supplementary Table S5. Additionally, it was assumed that 80% of the imported HEVs are

TABLE 3 Parameters used in the Weibull distribution.

Product	Average Lifespan (λ)	Shape Parameter (k)	Source
HEV	19.1 years	3.6	Mendjargal et al. (2022)
NiMH	15.6 years	1.95	Yano et al. (2016)
BEV/LIB	12 years	3.5	Rettenmeier et al. (2025)

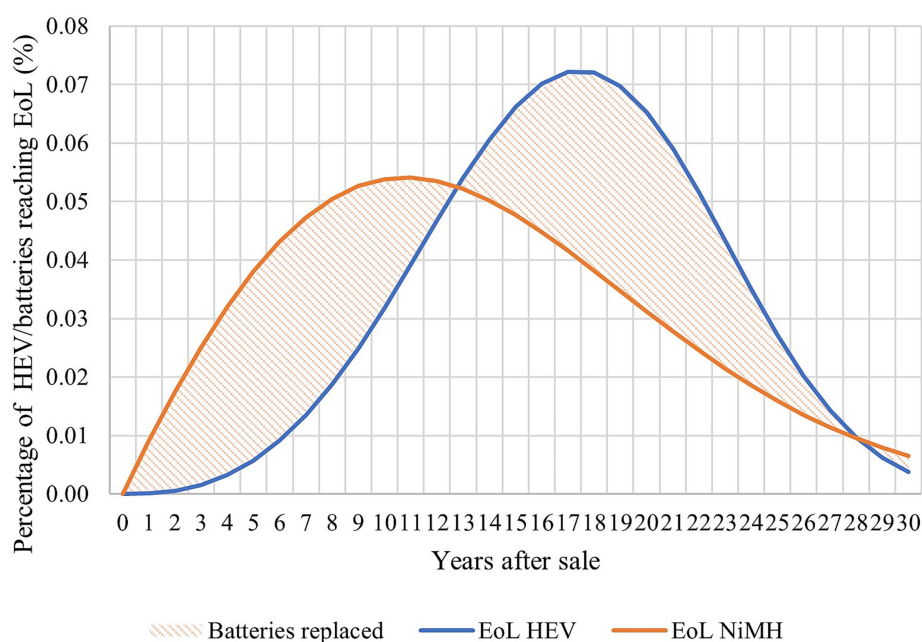


FIGURE 1

Comparison of lifespan distribution of HEV and NiMH. Source: Own compilation based on Weibull distribution.

second-hand vehicles with an average age of import of 8 years (UNEP, 2020, 2021; Mendjargal et al., 2022; ITF, 2024).

Based on documented market developments, 5th-generation Toyota Prius HEVs, available in the market from 2023, solely utilize LIB technology (Toyota, 2024). The characteristics of the batteries adopted to calculate the weight of the end-of-life batteries are shown in Table 4.

Because an official time series of observed EoL automotive battery outflows is not available in Mongolia, predictive performance is assessed at the vehicle-fleet projection stage through out-of-sample backcasting (MAPE reported in Section 3.3 and detailed in the Supplementary material), while EoL battery outflows are scenario- and parameter-dependent projections of the lifetime and battery-specification assumptions.

In sequence, based on the quantities of EoL batteries generated in both scenarios (Current Policies and Climate Focus), different EoL battery management scenarios were constructed (Table 5) to develop the MFA. The scenarios varied in the collection, reuse, recycling and disposal rates, aiming to allow comparison of the different potential material recovery and to illustrate a gradual evolution from the baseline to the best-case scenario. Table 5 shows the values used to define each scenario. Each column is a scenario, and each row is a parameter.

The Material Flow Analysis system boundary included the usage, replacement and EoL NiMH and LIB from EVs within Mongolia. The analysis is static and represents the volumes in the year 2050. Only material flows are considered, excluding energy use, emissions, and other environmental impacts. The system encompasses processes related to the collection, repair, reuse, recycling, and disposal of spent NiMH and LIB batteries, tracing the flows of the battery materials. The functional unit of the study is one metric ton of material, providing a standardized basis for quantifying and comparing material flows. This

TABLE 4 Adopted battery pack chemistry and weight.

Battery chemistry	Toyota Prius (HEV)		Nissan Leaf (BEV)
	NiMH	LIB	LIB
Weight (kg)	39	32	303
Source	Toyota (2004)	Toyota (2012)	Nissan (2022)

boundary definition aims to support the assessment of material recovery potential and waste management strategies for EoL batteries in Mongolia's future context.

3.3 Data

The study is based on information collected from local stakeholders, including the Ministry of Road and Transport of Mongolia (MRT), National Environment Pollution Control Committee, Mongolian University of Science and Technology, Green Growth Global Initiative (GGGI) and by field research at collection points, repair shops, and landfill sites. The annual vehicle fleet in Mongolia was obtained from the Ministry of Road and Transport and the National Statistic Office (NSO) database, which was available from 2010 to 2023. While discrepancies were identified between the two datasets, such as mismatched figures for passenger vehicle counts and occasional data gaps, these were critically assessed and documented. Mongolian population data projections were collected from the United Nations Statistics Division (UNSD) to calculate vehicle per capita.

Since the detailed distribution of vehicle models was unavailable, a recurrent issue in Global South countries (World

TABLE 5 EoL battery management scenarios in 2050.

Parameter (definition)	Scenario				
	Base line	Scenario 1	Scenario 2	Scenario 3	Best-case
Collection rate (% of total generated)	25%	25%	50%	90%	100%
Second use (% of collected generated)	No reuse	No reuse	20%	44%	70%
Recycling (% of collected, incl. Post-2nd use where applicable)	No recycling	10%	40%	42%	100%
Landfill disposal (% of collected + recycling residues)	0	90%	40%	14%	Recycling residue
Irregular disposal (% of total generated)	75%	75%	50%	10%	0
Export (% of total generated)	25%	No Export	No Export	No Export	No Export

TABLE 6 Number of imported cars by country and year.

Country of origin	2019	2020	2021	2022	% of total imports
Japan	65,372	49,779	52,014	60,160	91.7%
China	54	128	239	1,550	2.4%
Republic of Korea	1,295	840	876	1,094	1.7%
Germany	845	719	595	924	1.4%
United States of America	485	569	614	823	1.3%

Source: NSO (2025c).

Bank, 2022), representative battery specifications were assumed considering the most prevalent models in Mongolia: NiMH batteries in HEVs were modeled based on the Toyota Prius Gen 2, LIBs in HEVs on the Toyota Prius Gen 5 (NMC chemistry), and LIBs in BEVs on the Nissan Leaf, which also uses NMC chemistry. This unavailability reflects structural data limitations of vehicle information in Global South contexts, where vehicle registration and trade datasets are aggregated and do not report model-generation or battery-specific attributes (e.g., chemistry/pack specification), and where used-vehicle trade data can be incomplete or inconsistent across sources (ITF, 2023; UNEP, 2024; World Bank, 2022). Therefore, results related to battery mass and chemistry should be interpreted as estimates based on a representative-model approach rather than a fully model-disaggregated characterization of the national fleet; improved data availability would allow refinement of results in future work.

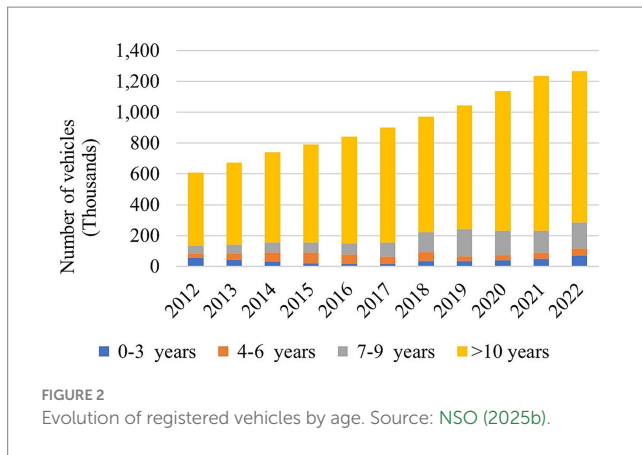
Nevertheless, to support assessment of forecast reliability, the historical passenger-vehicle fleet and population series (2010–2023) were used for out-of-sample backcasting of the vehicle-fleet projection module that underpins the EoL outflow calculations. The vehicle-per-capita relationship was calibrated on 2010–2018 and applied to predict the hold-out period 2019–2023 using the observed population in each year. Predictive performance was quantified using the Mean Absolute Percentage Error (MAPE). Detailed year-by-year calculations are provided in the Supplementary material. Over the 2019–2023 hold-out period, the fleet projection achieved MAPE = 4.71%. According to Lewis (1982), MAPE < 10% is considered a highly accurate forecast. Therefore, the 4.71% MAPE indicates a highly accurate fit for the vehicle-fleet projection over the 2019–2023 backcasting period.

4 Results

4.1 Mobility development in Mongolia

According to the National Statistic Office (NSO) data and the Ministry of Road and Transport (MRT), there has been a constant increase in the total number of registered passenger vehicles in Mongolia since 1997. Regarding the evolution of the distribution of different types of vehicles namely, battery electric vehicles (BEV); hybrid electric vehicles (HEV); internal combustion engines (ICE) with diesel (ICE-D), gasoline (ICE-G) and natural gas (ICE-NG), even though gasoline-fueled vehicles have been predominant over the years, there has been a constant increase in hybrid vehicles and, more recently, electric vehicles. Data from 2021 and 2022 show a significant increase in electric vehicles (+37.73%) and hybrid vehicles (+13.48%) (NSO, 2025a). Mongolia's government has been incentivizing BEV by exempting such vehicles from Road User Charges (RUCs) and road space rationing regulations (i.e., odd-even license plate usage restriction meant to reduce daily vehicle congestion) (MRT, 2021).

According to data from NSO (2025c), Mongolia mainly imports vehicles from Japan, particularly Toyota Prius HEVs, which comprise more than half of all used vehicle imports to Mongolia (Table 6). Even though market shares are still smaller, imports from China are growing rapidly, as the increase by 549% between 2021 and 2022 shows. As stated in a report from MRT, “more than 99% of all vehicles are imported, leading to the inevitable choice of electric cars in the future” (MRT, 2021). Therefore, it is expected that Mongolia will continue to serve as a destination for used EVs in the future (JARC, 2021).



The popularity of used vehicles in Mongolia can be explained by the population's moderate average purchasing power. According to Wang and Okubo, (2019), the age of HEVs imported to Mongolia from Japan typically ranges between 10 and 15 years (Wang and Okubo, 2019). This results in a fleet with more than 77% of the vehicles aged above 10 years in 2022, as shown in Figure 2. For example, first-generation Prius vehicles are still being driven in Mongolia, even though they are 18–23 years old (Mendjargal et al., 2022).

According to the methodology explained in Section 3, the number of vehicles registered from 2010 to 2023, together with the UNSD population forecast (Figure 1 in Supplementary material), was used to forecast the number of total passenger vehicles from 2023 to 2050. The historical data showed that the number of vehicles per capita in Mongolia grew linearly between 2010 and 2023 ($R^2 = 0.9865$; Figure 3), following Equation 3.

$$\text{Vehicle per capita}(i) = 0.0106(i) - 21.225 \quad (3)$$

Where: i = year.

The result is shown in Figure 3 and compared with the development of the Mongolian Gross Domestic Product (GDP) forecast from IMF (2025).

As Mongolia has recently experienced an increasing Gross Domestic Product (GDP) (a parameter proven to have a moderately strong relationship with the number of vehicles in use) and has not yet reached vehicle market saturation (generally around 0.6 vehicles/capita for middle-income countries; World Bank, 2022), the results were considered to be in an adequate range. As a result, it is estimated that in 2050, Mongolia's passenger vehicle fleet will reach 2,432,802 vehicles (Supplementary Table S2).

As explained in the method section, the distribution of electric and hybrid vehicles used in this study is based on the final targets of the decarbonization scenarios from the International Transport Forum (ITF, 2023). Two pathways were defined: Current Policies and Climate Ambition, the latter renamed here as the Climate-Focus Scenario. These scenarios include not only the adoption of low-emission vehicles but also improvements in public transport and the promotion of shared and active mobility. Figure 4 was constructed by using the vehicle fleet distribution from 2024 to 2050 (detailed in Supplementary Table S3). By 2050, the Current Policy scenario targets 16.3% Battery Electric Vehicles (BEVs) and 2.1% Hybrid Electric

Vehicles (HEVs), while the Climate-Focus scenario aims for 49.2% BEVs and 4.6% HEVs.

The analysis of two scenarios, a conservative and a more ambitious approach to e-mobility development in the country, provides a clearer understanding of potential pathways and supports more informed and resilient policy recommendations.

4.2 End-of-life battery management in Mongolia

4.2.1 Legislation and responsibilities

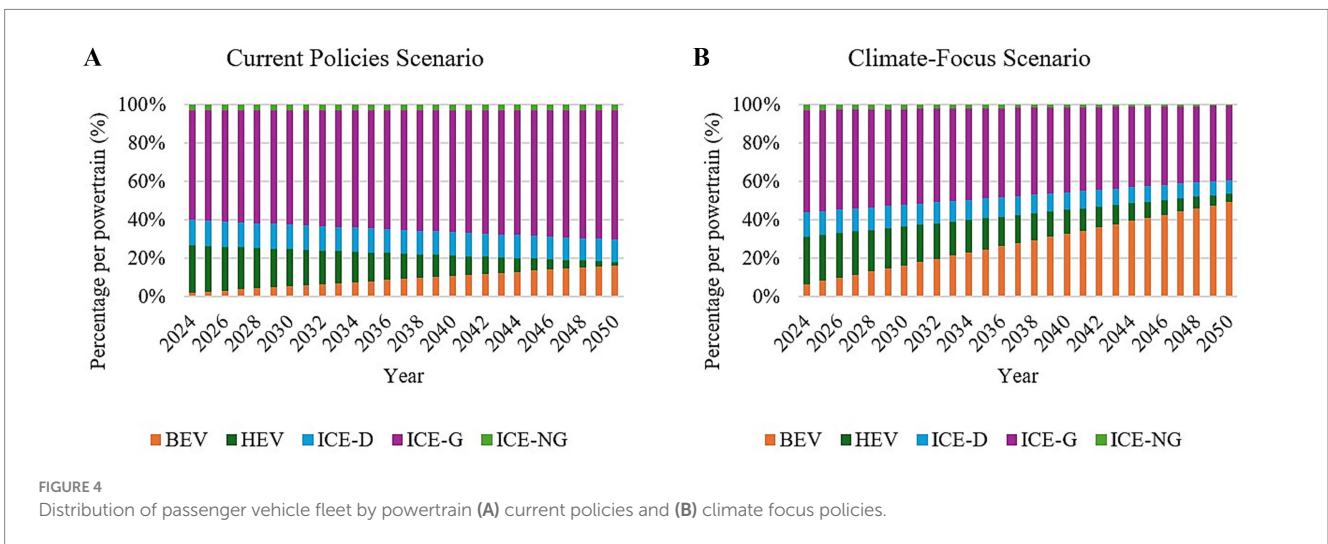
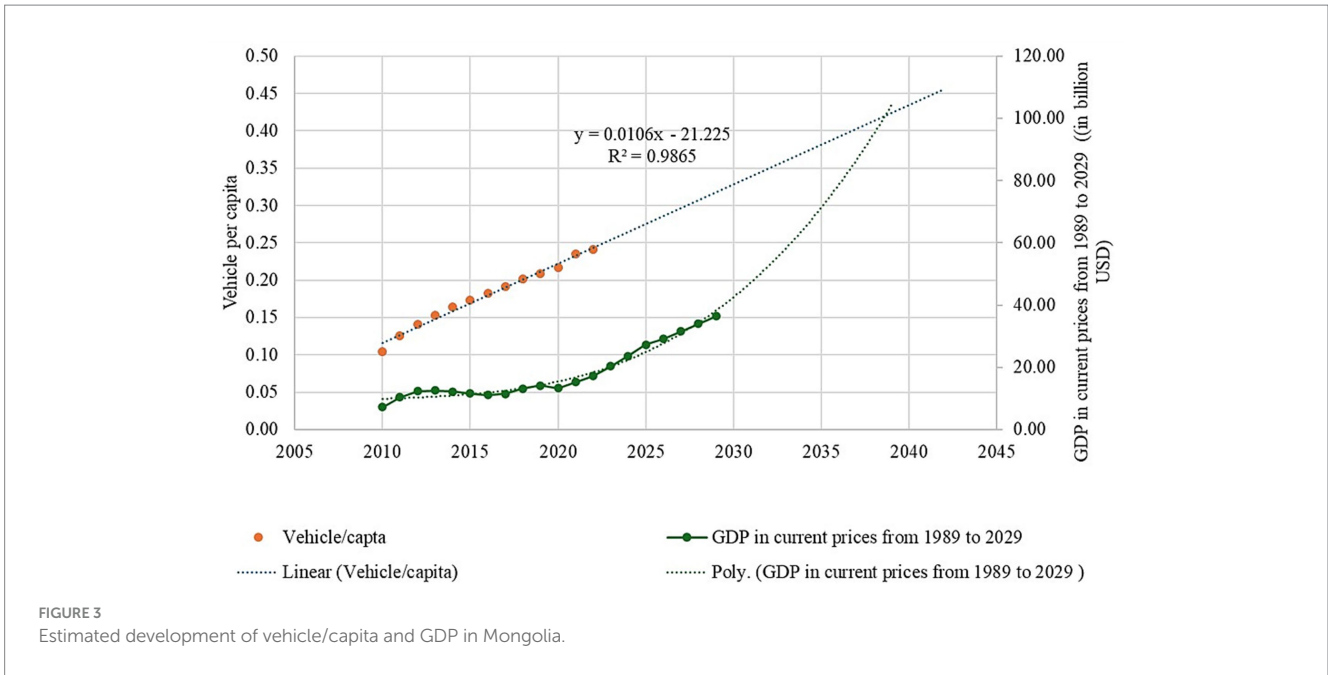
In Mongolia, solid waste management is governed by a comprehensive framework of laws, regulations, standards, programs, and guidelines designed to promote sustainable practices throughout the country. A summary is presented in Table 7 and its key aspects are described below.

The 2017 Law on Waste Management aims to “regulate aspects of reduction, sorting, collection, transportation, storage, reuse, recycling, recovery, disposal and export of waste, and prohibition of hazardous waste import and cross-border transportation to reduce and prevent adverse impacts of waste on human health and the environment, putting waste into economic turnover, saving natural resource and wealth, and raising public awareness of waste”. Additionally, its seven chapters define the responsibilities of governmental bodies, citizens, businesses, and organizations. It calls for the creation of an Integrated Waste Database and training of waste producers in the identification and classification of waste and hazardous waste. However, so far, it has only been poorly implemented.

Aiming to support the implementation of the Waste Law of 2017, the Mongolia National Waste Management Improvement Strategy and Action Plan (2017–2030) was published shortly after. Relevant aspects regarding end-of-life vehicle battery management included in the plan are described below:

- Improve the legal framework to facilitate better law enforcement to achieve sustainable waste management.
- Execution of studies on different waste streams, including automobile batteries, and develop regulations, guidelines and waste management plans for each type of waste”
- Establish a legal framework for the manufacturers and importers, define responsibility for the waste generated from their products/goods, and monitor waste imports.
- Establish regulations to monitor, restrict, or prohibit imports of second-hand goods, e.g., electronics and automobiles.
- Creating Extended Producer Responsibility (EPR) based regulations where importers and manufacturers are legally, physically, and financially responsible for solid wastes generated from their imported or domestically made products.
- Improving the legal framework for managing hazardous waste, including emerging waste types such as automotive batteries.

It is important to highlight that Mongolia has been a signatory to the “Basel Convention on the Control of Transboundary Movement of Hazardous Wastes” since 1996. As per the obligation of a party to the Basel Convention, the Ministry of Nature, Environment and Tourism (MNET) organizes control and tracking of transboundary



transportation of hazardous waste together with the recipient country’s Ministry in charge of the environment.

Mongolia’s Action Plan for 2021–2030 of Mongolia’s Long-Development Policy “Vision-2050,” published in 2020, reinforces the need to transition toward more sustainable waste management (Mongolia, 2020a). For the short-term, development guidelines were published in 2020, Mongolia’s Five-Year Development Guidelines for 2021–2025, which included the objectives to increase waste recycling to 27%; build waste recycling factories; introduce technological innovations in waste sorting, collection and transportation services; and create a system to support low-emission and waste-free consumption (Mongolia, 2020b).

Even though the Integrated Database was instituted by Law in 2017, and waste data has been collected, its accessibility and quality are low (United Nations, 2018). As previously highlighted for the mobility sector, the lack of waste management data hinders the development of coherent projects and policies. In addition, the

priority in waste management during the last decade has been the improvement of municipal solid waste (MSW) management and healthcare waste management, and sectoral waste management strategies (such as for automotive batteries) have not yet been developed (United Nations, 2018).

4.2.2 EoL battery generation

The definition of adequate waste management strategies depends highly on the quality and quantity of the waste stream to be handled (Lebreton and Andradý, 2019). Nevertheless, until today, no official database records the quantity and quality of EoL automotive batteries generated in Mongolia. The work of Wang and Okubo, (2019) estimated the number of NiMH batteries reaching EoL by 2030. According to the study, in 2030, 71,000 units of NiMH (equivalent to 2,769 tons of EoL NiMH for a 39 kg battery pack) will reach end-of-life if the battery lifespan is extended to 20 years (Wang and Okubo, 2019). However, if the lifespan is reduced, the number of EoL batteries

TABLE 7 Mongolian solid waste management legislation.

Year	Legislation title	Type	Important aspects
1999	Waste reduction program	Program	HW General requirements
2001	Codified list and rules of prohibited and licensed goods for importing across border	Regulation	*HW is prohibited to import
2006	Classification of hazardous waste (HW)	List	*16.06 – Battery, accumulator (Pb, Ni-Cd, Hg)
2014	National program to improve waste management	Program	HW General requirements
2017	Waste law	Law	*Flammable and reactive waste cannot be landfilled
2017	Mongolia National Waste Management Improvement Strategy and Action Plan from 2017 to 2030	Action plan	*Conduct studies on e-waste, waste automobile batteries, and develop regulations, guidelines and waste management plans
2018	Regulations for temporary storage, collection, transportation, recycling, disposal and registration and reporting of hazardous waste	Regulation	HW General requirements
2020	Regulations for cleaning, collecting, sorting, transporting, recycling, reusing, destroying and burying vehicle waste	Regulation	HW General requirements
2021	Action plan for 2021–2030 of Mongolia's long-term development policy "Vision-2050"	Action plan	General goals to improve waste management
2022	UCS 1703A:2022- Hazardous Waste Management	Standard	Detailed requirements for HW management

is much higher, reaching 160,000 units (6,240 tons) (Wang and Okubo, 2019). Differently from Wang and Okubo, (2019), our work extends the projection of NiMH batteries for 2050 and includes a projection of EoL LIBs. The yearly EoL battery volumes were calculated through a multi-step process: First, the Weibull probability density functions (Equations 1, 2) were applied to the annual vehicle sales data (Supplementary Table S5) to determine the timing of battery retirement. Second, the resulting EoL battery units were converted into mass by multiplying by the respective battery weights presented in Table 4 (39 kg for NiMH, 32 kg for LIB in HEVs, and 303 kg for LIB in BEVs). Third, the transition from NiMH to LIB in new HEVs from 2023 onwards was incorporated based on documented market developments (Toyota's 5th generation Prius launch with lithium-ion technology). The calculation accounts for different battery lifespans (15.6 years for NiMH, 12 years for LIB) and vehicle lifespans (19.1 years for HEVs), with battery replacement occurring when battery lifespan is shorter than vehicle lifespan. The results are presented separately for both policy scenarios to illustrate the impact of different EV adoption rates on future battery waste streams, as shown in Figure 5.

The higher EoL battery volumes under the Climate-Focus scenario are an expected outcome of a higher EV uptake (a larger BEV/HEV sales necessarily translates into larger quantities of future EoL battery). Importantly, these higher quantities indicate a requirement for greater collection, storage, and treatment capacity to avoid environmental and human health hazards at battery end-of-life and also indicates a larger potential for circular strategies (e.g., second use and metal recovery) that may improve the economic feasibility of reverse logistics and recycling infrastructure (Ai et al., 2019; Harper et al., 2019).

As can be seen, in the Current Policy scenario, the quantity of End-of-Life batteries generated in 2050 is estimated to be 6,172 tons of EoL LIB and 26 tons of EoL NiMH generated, and for the Climate Policies scenario, it is expected to be 17,613 tons of EoL LIB and 30 tons of NiMH EoL batteries. The very low values of NiMH in 2050 are due to the expected transition from NiMH to LIB in HEV. The peak of EoL NiMH batteries occurs in 2034, when 608 tons are expected to

be disposed of under the Current Policies Scenario and 617 tons for the Climate Focus Scenario. Cumulatively (from 2023 to 2050), in the Current Scenario, 10,302 tons of EoL NiMH and 54,841 tons of EoL LIB are generated, whereas for the Climate Focus Scenario, 10,455 tons of EoL NiMH and 151,361 tons of EoL LIB are expected. A comparison is shown in Figure 6.

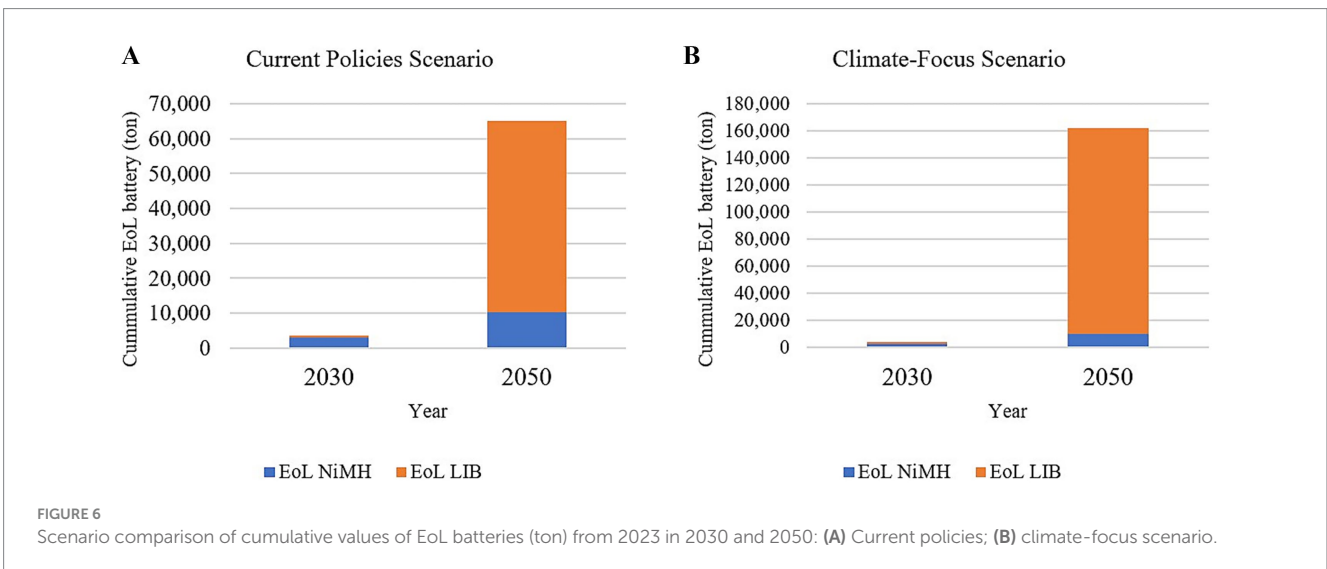
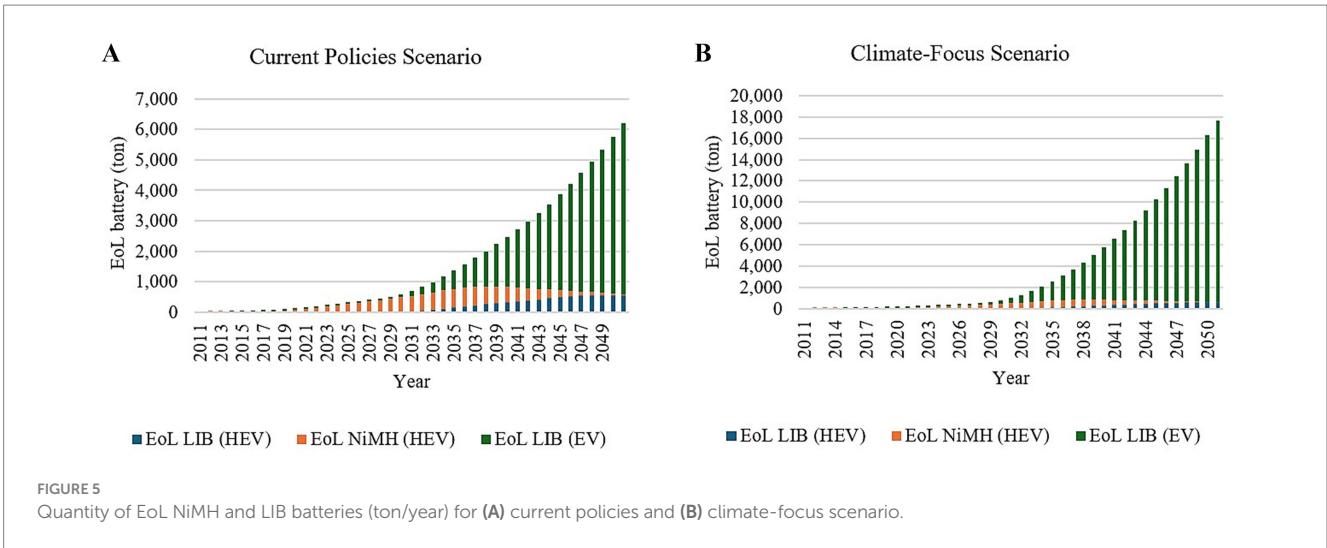
Interesting to note that when looking at the values of EoL NiMH for 2030, we have obtained a much lower result than Wang and Okubo, (2019), even when the authors considered a longer lifespan of the batteries (15 years). The difference between our 2030 NiMH estimates and Wang et al. (2019) reflects modeling choices, particularly the incorporation of the transition from NiMH to LIB in HEVs after 2023 and the different lifespan adopted. This comparison allows to understand how alternative lifespan and technology-transition assumptions affect projected EoL volumes.

4.2.3 Collection

Mongolia has no well-established collection system for recyclable material and special waste streams. Informal workers play an important role in collecting recycled materials (UNEP-IETC, and GRID-Arendal, 2019). The waste pickers take the collected material to known "collection points" (shown in Figure 7) where it is weighed and they are paid according to the weighted amount and value of the material. According to the Mongolian National Recycling Association (MNRA), 10 collection points receive end-of-life batteries. Due to its informal characteristic, estimating the quantity of batteries being collected is difficult.

The used battery modules are then stored in the collection centers (Figure 8) and are further sold to exporting companies for 500 Mongolian Tugrik (MNT; approx. 0.15 USD).

As Mendjargal et al. (2022) pointed out, the collection of used automotive batteries is considerably more complicated than usual because most used vehicles are first utilized in the capital city and then resold to buyers in more remote provinces. The significant geographic distance and low population density in these areas increase the cost of collection and transportation.



4.2.4 Treatment

4.2.4.1 Repair

In Ulaanbaatar, Mongolia, many repair shops specialize in refurbishing Toyota Prius and other HEV batteries. These repair shops (shown in Figure 9) analyze each module of the battery, replacing defective ones for an average market price of MNT 30,000 (approx. 9 USD) per module; however, rebalancing the battery pack may be less of a priority (GIZ, 2022).

So far, Mongolia has no standard or guidelines for checking, storing, or processing EoL automotive batteries. In the case of traction batteries, this may lead to a reduction in the quality and lifespan of refurbished batteries (GIZ, 2022). During stakeholder interviews with the National Environment Pollution Control Committee, it became clear that there is no reliable record of the exact number of repair shops in Ulaanbaatar. However, it was pointed out by the Committee that most do not have environmental licenses, and no Environmental Impact Assessments were conducted before their establishment, despite a legal requirement for such procedures. During field research, it was noted that the repair shops also sell EoL



battery modules to exporting companies for a fixed price of 500 MNT (0.15 USD).



FIGURE 8
End-of-life battery storage in collection points. Source: Prates et al. (2023). (authors' own archive).

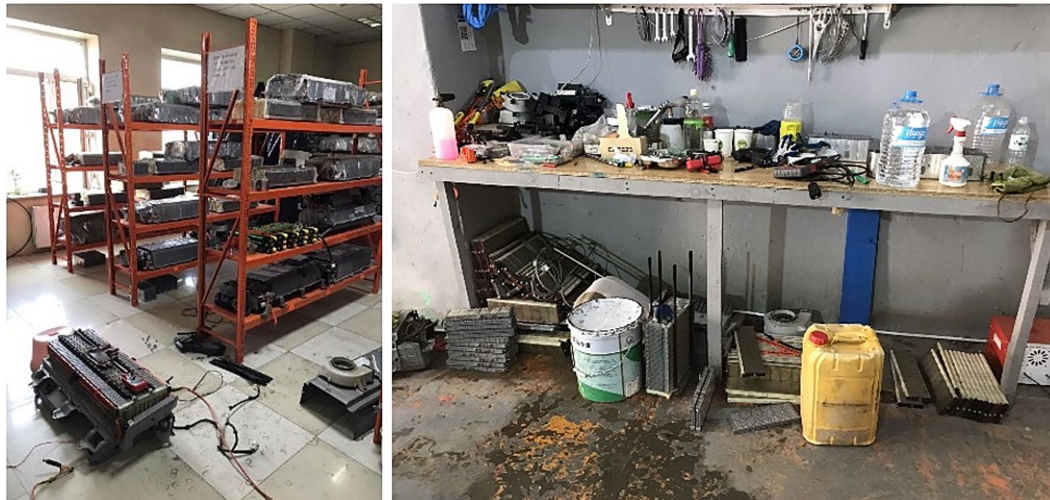


FIGURE 9
Repair shops in Ulaanbaatar. Source: Prates et al. (2023). (authors' own archive).

4.2.4.2 Reuse

In literature, many studies have advocated for reusing end-of-life vehicle batteries in stationary energy storage applications or in battery remanufacturing (Kotak et al., 2021; Wang et al., 2021b). Repurposed NiMH and LIB packs could have significant positive environmental impacts and offer an alternative to remote households, such as those of nomadic herders in Mongolia. Today, most of these settlements use lead-acid batteries to power their solar systems (Figure 10). Compared to LIB, lead-acid batteries have lower charging rates, energy density, lifespan, and a very problematic environmental footprint (Podder and Khan, 2016) if not disposed of properly. However, the most significant advantage of lead-acid batteries today is their higher affordability (Podder and Khan, 2016).

As pointed out in many publications, battery repurposing is complex and requires highly specialized knowledge to guarantee these batteries' secure processing and second-life usage (Seika and Kubli,

2024). In addition, it was noted by the study of GIZ (2022) that the residual charge of batteries entering the waste stream in Mongolia is lower than expected due to their condition when imported into the country. In summary, even if there is an opportunity for reuse, its feasibility may be challenged by safety aspects, infrastructure, logistics, technical capacity, costs, and post-consumer aspects (collection and proper disposal).

4.2.4.3 Recycling

Until today, Mongolia has no operational recycling facility for handling end-of-life NiMH and LIB. However, the recycling industry for lead-acid batteries exists, and it produces lead plates as a final product (International, B, 2024).

The Mongolian National Recycling Association (MNRA) was established in 2005, and it is a Non-Governmental Organization (NGO) that aims to develop Mongolia's waste management and recycling industry, including the informal sector. According to a



FIGURE 10
Solar panels used in Mongolian gers (A) and lead acid batteries used as energy storage systems (B). Source: Prates et al. (2023). (authors' own archive).



FIGURE 11
Preparation of NiMH modules to be exported. Source: Prates et al. (2023). (authors' own archive).

representative of MNRA interviewed, key challenges to improving the recycling sector include: difficulties for companies in the sector to obtain an environmental license; customs taxes are too high to import the necessary machinery for recycling; the government does not encourage or enforce recycling activities; and, in addition, a lack of environmental awareness hinders the collection of recyclables.

4.2.5 Export

Two companies that export NiMH battery modules were interviewed. The respective company owners stated that the export of batteries was not their primary business, and that they started their exports in 2016 and 2022. Both companies stated that they exported used batteries to Japan through Russia, following import regulations from Japan. Despite Mongolia being a signatory to the Basel Convention, the perception of the EoL battery exporters was that there were no export regulations from the Mongolian side. Nevertheless, it is important to clarify that, as Mongolia has borders only with China and Russia, and both countries are part of the Basel Convention, the export of hazardous waste is forbidden (Mendjargal et al., 2022). Figure 11 below shows the procedures for packing and storing the batteries for exporting.

When questioned about the opportunities and challenges regarding the export of end-of-life batteries, the companies saw two key opportunities: being the “only company that exports and having exclusivity” and “helping Mongolia to prevent environmental pollution.” Challenges identified by the companies included a lack of support from the government, the presence of illegal exporting companies, batteries lost in rural areas, cultural issues (many Mongolians want to keep EoL batteries due to their “value”), and unregulated repair shops that do not dispose of their batteries adequately.

Based on interviews with two exporting companies, an estimated total of 130,000 NiMH battery modules were exported from Mongolia in 2020 (Company 1: approximately 70,000 modules; Company 2: approximately 60,000 modules). According to Wang and Okubo, (2019), approximately 20,000 end-of-life (EoL) NiMH battery units were generated in Mongolia in 2020, assuming a 15-year battery lifespan. Given that each battery unit contains 28 modules, this corresponds to 560,000 EoL NiMH modules. Therefore, it can be estimated that around 23% of the EoL NiMH battery modules generated in Mongolia in 2020 were exported to Japan. The export of used NiMH batteries to Japan is not exclusive to Mongolia, and other



FIGURE 12
Landfill site. Source: Prates et al. (2023). (authors' own archive).

countries, such as Thailand also follow this same approach (Suriyanon et al., 2022).

In 2015, Japan's Ministry of Foreign Division, in collaboration with the Ministry of Economy and Industry and Nippon Steel and Sumikin Research Institute Corporation, conducted studies on recalling and recycling HEV batteries exported to Mongolia (GIZ, 2022). They concluded that Mongolia should collect HEV battery waste so that Japan can import and recycle it. Additionally, the Mongolian government has been negotiating with Japan regarding taxes on exported cars that the Japanese government keeps. In Japan, a vehicle recycling tax is included in the car's market price, which Mongolian buyers also pay when importing these cars. Discussions have been ongoing about reallocating the accumulated funds from these taxes to the Mongolian government (GIZ, 2022).

4.2.6 Final disposal

Since not all disposal units in Mongolia could be assessed, Ulaanbaatar disposal sites were used as a reference. The city has three landfill sites outside the city. These landfills have no facilities for leachate treatment or mechanisms to prevent its infiltration into the ground, and waste burning is common in the landfill site (Gombojav and Matsumoto, 2023). During the research trip to one of the landfill sites (Figure 12), the presence of waste pickers in the operational front was observed. It is assumed that the EoL batteries that are not collected and exported are either landfilled or dumped in other inappropriate sites.

4.3 MFA scenarios

In sequence, the MFA of EoL LIB and NiMH batteries in Mongolia were obtained for each scenario in the year 2050. To construct the MFA all the flows were calculated based on the assumptions defined in Table 5. To calculate the potentially recoverable mass of each material through recycling processes, the recovery efficiencies used are detailed in Table 8. These efficiencies were based on Takano et al. (2022); López Hernández et al. (2024); Clyde et al. (2025).

As a result, the potential quantity of recovered metals was calculated, and Table 9 shows the cumulative values of recovered materials from EoL batteries from 2023 to 2050 in all scenarios.

TABLE 8 Metal recovery efficiencies of LIB (NMC) and NiMH.

LIB (NMC)		NiMH	
Metal	Recovery efficiency	Metal	Recovery efficiency
Al	95%	Al	100%
Co	100%	Co	90%
Fe	100%	Fe	100%
Ni	100%	Ni	87%
Mn	100%	Mn	100%
Cu	100%	Nd	98%
Lithium	98%	La	99%
		Ce	99%
		Pr	98%

The material flow analysis was generated using the STAN software by inputting the calculated material flow values for each pathway across the respective scenarios. It was assumed that no stock accumulation occurred at repair shops or collection points due to the low retention time. However, a stock was introduced when batteries were reused in second-life applications. These reused batteries were assumed to have a second-life duration of 10 years, based on estimates from Akram and Abdul-Kader (2024). Figure 13 shows the MFA for the best-case scenario for the Current Policies, and the diagrams for other scenarios can be found in the Supplementary material. In-depth discussion and analysis of the MFA is detailed in Section 5.

5 Discussion

As a summary of the results and to support the discussion, Table 10 presents the current standpoint of Mongolia regarding the transition to electric mobility and the circular economy.

To enhance the circularity of end-of-life battery management in Mongolia, all stages of the waste management chain (collection, storage, reuse, recycling, and final disposal) must be improved, including data collection and the development and reinforcement of current waste management legislation.

A comparative overview of the different management scenarios' outcomes is presented in Figure 14. To construct the Figure, the EoL battery volumes were aggregated into four main management steps: collection, recycling, reuse, and final disposal. The data were derived by applying the scenario parameters from Table 5 to the projected 2050 EoL battery volumes (6,172 tons LIB + 26 tons NiMH for Current Policies; 17,613 tons LIB + 30 tons NiMH for Climate-Focus scenarios). For each of the five scenarios (Baseline, Scenarios 1–3, and Best Case), material flows were calculated by applying the respective collection rates (25–100%), second use/reuse rates (0–70%), recycling rates (0–100%), and disposal rates, with all calculations verified to ensure mass balance compliance. The aggregated results illustrate the quantitative differences in EoL battery management outcomes across scenarios, enabling direct comparison of the potential impact of different policy approaches on battery waste treatment pathways and can serve as a reference to dimension the necessary infrastructure for each management stage. In the context of circular economy, the forecasted EoL battery volumes quantify the future load that waste

TABLE 9 Cumulative volume of material recovered from 2023 to 2050 (in ton).

Cumulative volumes of recovered material (2023 to 2050) in tons								
Metal	Current policies				Climate policies			
	Sc 1	Sc 2	Sc 3	BC	Sc 1	Sc 2	Sc 3	BC
Ni	276	2,207	4,172	6,255	631	5,094	9,902	12,578
Co	302	975	4,567	2,315	823	2,607	12,469	5,923
Al	299	2,389	4,516	5,460	819	6,557	12,402	14,689
Fe	141	1,126	2,127	2,899	352	2,829	5,424	6,653
Cu	228	1,821	3,441	4,125	628	5,025	9,498	11,223
Mn	87	697	1,317	1,696	228	1,829	3,483	4,198
La	13	106	200	469	13	110	259	466
Ce	4	28	53	124	3	29	69	124
Li	17	138	260	312	47	380	718	848
Nd	2	17	32	76	2	18	42	75
Pr	1	6	12	28	1	7	16	28

management system must handle. These volumes define the scale of the infrastructure and governance required. Circularity is then operationalized by allocating the forecasted quantities across collection, second use, recycling, and disposal pathways under each scenario (Table 5), generating the specific masses for each management stage (as shown in Figure 14). Therefore, the forecasting results provide the quantitative basis for evaluating how different scenario configurations translate into circular outcomes (e.g., battery reuse and material recovery) versus non-circular outcomes (landfilling and irregular disposal; Ai et al., 2019; Harper et al., 2019; Shafique et al., 2022).

As it can be seen, in 2050, volumes of batteries available from recycling vary from as low as 155 tons of NiMH and LIB in Scenario 1 (lowest collection rate) of Current Policies (lower e-mobility transition) up to 9,891 tons of NiMH and LIB in the Best Case Scenario (100% collection rate) of the Climate Focus (higher e-mobility transition). Today, LIB recycling facilities operate with capacities as low as 5 tons per month (60 tons per year) in Colombia (López Hernández et al., 2024). The work of Baum et al. (2022) reviewed LIB recycling companies and their respective volumes processed. The companies ranged from 110 tons/year (Recupyl using hydrometallurgy) to 50,000 tons/year (Redux using pyrometallurgy technology; Baum et al., 2022).

According to the study of Dunn et al. (2022), recycling processes became profitable in China at throughput levels of ~3,000 t/year for hydrometallurgical, ~3,000 t/year for direct recycling, and ~4,000 t/year for pyrometallurgical recycling of LIBs. It is important to highlight that these values vary according to several factors, such as energy, labor cost, and technology availability and that due to Mongolia's unique characteristics, these values will be different. Nevertheless, it can indicate thresholds at which it can be feasible to implement a recycling unit.

As a rough cost estimation, it has been calculated that implementing a hydrometallurgical recycling unit of 5,000 to 7,000 tons/year would require a capital expenditure (CAPEX) of approximately USD 10.15 million and a yearly operational expenditure (OPEX) of circa USD 1,560 per ton of cathode material processed (Dai et al., 2019). The study was conducted for India's reality; therefore, the

cost is expected to vary in the Mongolian reality. Nevertheless, such values are relevant to bear in mind and show that the Mongolian government should initially focus on previous stages of the waste management chain, such as collection, storage, and reuse.

In the short term, due to the lack of scale (and consequently higher operational costs and low revenue coming from selling the recovered materials), it is very challenging to have an economically sustainable recycling unit. It is important to remember that not only is the installation of the facility required, but the market development for recovered materials and proper collection and storage systems are necessary (Zeng, 2025).

The informal sector must be included in the process of improving the collection of the EoL batteries. The integration of informal and formal sectors has been identified as essential for creating sustainable waste management systems in developing economies, particularly for managing hazardous materials like batteries (Raghupathy and Chaturvedi, 2013). Other countries with high activity of waste pickers, such as Brazil, already have strategies to include these workers in the waste management system (Talbot, 2022). Through the establishment of associations, informal workers can be hired by the government (and companies) to provide collection, sorting, and storage services. The Brazilian National Solid Waste Policy explicitly mentions that "waste pickers should be integrated into actions involving shared responsibility for the life cycle of products" (Brasil, 2010). This supports the integration of informal workers and enhances collection rates. To achieve adequate results, the workers must be adequately trained and coordinated. The government can provide this training or coordinate with the Mongolian National Recycling Association (MNRA). Another strategy to increase collection rates is to work closely with the repair shops. Considering that in Mongolia, as in other Global South countries, it is very common to repair instead of discarding, repair shops play a central role in guaranteeing the safe collection of end-of-life batteries and creating awareness of how they should be handled at their end-of-life.

The relatively low number of end-of-life batteries and the poorly developed recycling sector in the country mean that regional or international collaboration in reuse and recycling is meaningful,

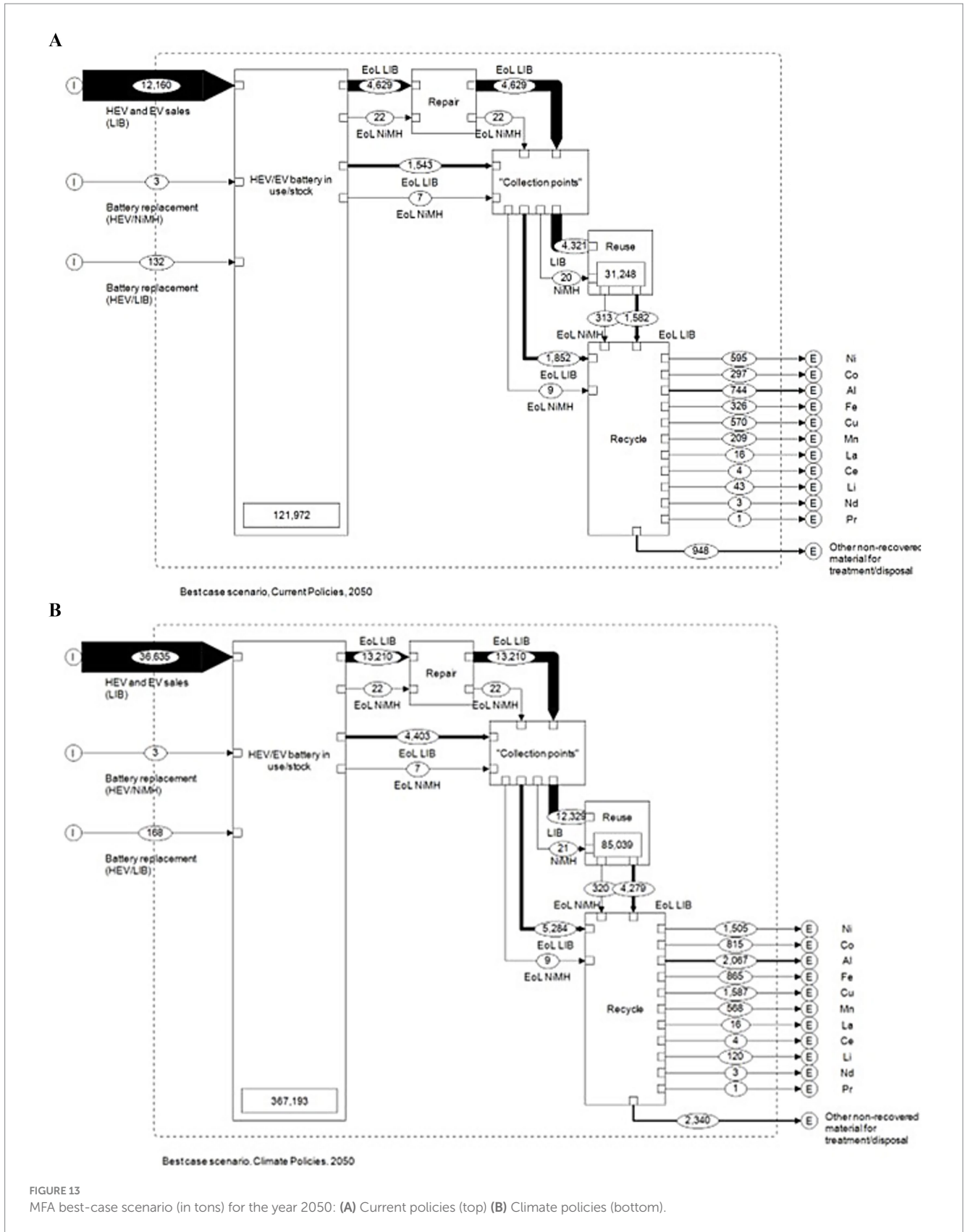


FIGURE 13 MFA best-case scenario (in tons) for the year 2050: (A) Current policies (top) (B) Climate policies (bottom).

especially in the short term. This requires structured schemes to optimize logistics and responsibility. In this sense, it is necessary to clearly define the responsibilities. As Japan is the key provider of used

HEV to Mongolia and the country has been receiving EoL battery modules to treat, strengthening collaboration with Japan currently plays a key role in closing the loop for EoL battery packs. This aligns

TABLE 10 Summary of E-mobility transition and circular economy transition.

E-mobility transition	Circular economy transition
<ul style="list-style-type: none"> • Initial stage of BEV adoption in Mongolia and moderate uptake of HEV; • Low charging infrastructure in the country • Developed sector to repair HEV batteries, but non-existent sector for BEVs; • Barrier for adoption: Low BEV driving range; • Vehicles are mainly imported from Japan; • Chinese vehicles are entering the market; • Air pollution is a big issue in UB and a motive to support BEVs adoption; • The Ministry of Road and Transport is key to promoting the e-mobility transition; • Financial incentives for BEV/HEV adoption are in place; • Lack of proper fleet data collection. • Climate change debates pressure to mitigate GHG: BEV adoption as easier solution. 	<ul style="list-style-type: none"> • Linear system of HEV EoL battery (low collection, no recycling, landfill disposal); • Informal collection system; • Inappropriate storage at collection points; • Battery modules are being exported to Japan; • Governmental sectors are aware of the problem but do not have information; • No effective EPR system in place; • Lack of environmental legislation enforcement; • Low economic development (waste management is not a priority) • Lack of proper waste data collection. • Resource scarcity is a driver for recycling EoL batteries (Japan); • International movement toward a circular economy.

with Japan's goal to secure scarce materials to enhance battery production (Sato and Nakata, 2020).

As can be seen in the cumulative values of metals that can be potentially recovered from 2023 to 2050 (Table 9), when looking at the Climate Focus Scenario, it can reach up to 12,578 tons of Ni, 14,689 tons of Al, 11,223 tons of Cu, 5,923 tons of Co and 848 tons of Li. Even though on a global scale these values might seem low, when improperly disposed of, they can cause severe damage to human health and the environment (Prates et al., 2023). Additionally, the increasing demand for nickel and cobalt may lead to a supply-demand gap in the future (Chen et al. 2022). The study of Li et al. (2025) predicts that the demand for Ni resources will reach 500–700 kt by 2040, also foreseeing potential future supply chain disruptions. The authors also predict a trend toward a 'high Ni low Co' battery cathode material chemistry, to move away from cobalt, which can further increase Ni's criticality. Therefore, all the efforts to recover and recycle EoL and the development of alternative sustainable materials for batteries are very relevant. It is important to highlight that future technological breakthroughs can change battery chemistries to less critical materials (eg, sodium-ion batteries) and require stronger regulations and additional incentives for recycling (Hasan et al., 2025).

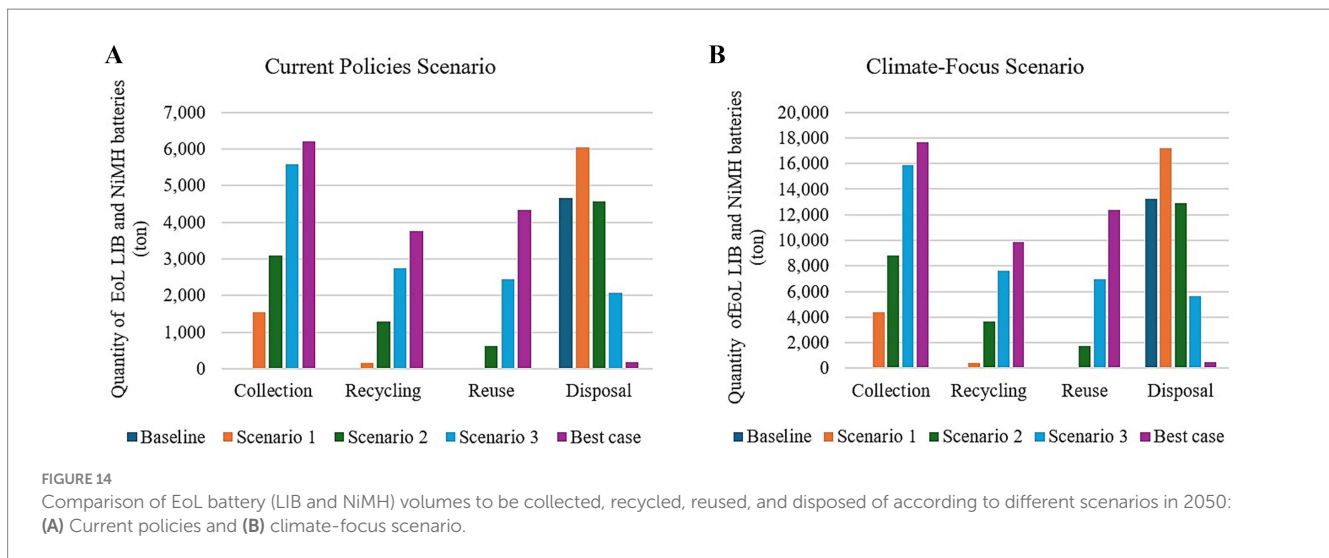
By comparing Scenario 1 (lower collection rate and high irregular disposal) between the Current Policies and Climate Focus scenarios, it is interesting to note the differences (and potential risk) that an accelerated e-mobility transition can bring if the waste management system is poorly developed. In this scenario, the quantity of irregular disposal in 2050 is 6,046 tons of EoL batteries for the Current Policies. In contrast, for the Climate Focus scenario, it reaches 17,202 tons of batteries, significantly increasing the environmental pollution. This comparison illustrates that faster fleet electrification increases circularity gains only if collection, storage and recycling capacity develops accordingly, otherwise, higher EoL battery volumes amplify non-circular outcomes and environmental risk.

Regarding the legislation aspect, even though Extended Producer Responsibility (EPR) is foreseen in the Waste Management Law of 2017, it is not yet in place. Previous work by Murun (2015) suggested that the implementation of EPR in Mongolia should be a mandatory scheme implemented by the government. A Producer Responsibility Organization (PRO) should be established to centralize the collection, storage, reuse, recycling, and disposal of end-of-life automotive batteries. The author also suggests that national or municipal

governments can support this by allowing the PRO to utilize existing infrastructure. An independent player should monitor the EPR scheme to certify the system's efficiency (Murun, 2015).

When looking specifically at automotive batteries from imported used vehicles, the international character of the players in the EPR scheme enhances the implementation challenges. The biggest issue surrounding EPR in international trade is the limits of the producer's responsibility and whether it should go beyond national borders. Even though theoretically, the responsibility for the end-of-life product should be transferred to the importer, considering the discrepancy between the development of solid waste management systems and the existence of illegal trade of waste, it is clear that a revision of the EPR is required. In such a context, EPR must create strategies to avoid pollution and responsibility shifting from developed to developing countries. More expanded EPR concepts were suggested by Li et al. (2013) and Thapa et al. (2023), which were, respectively, the Full Extended Producer Responsibility and the Ultimate Producer Responsibility (UPR). The Full Extended Producer Responsibility states that the producer is not only responsible for the take-back process in its own country but is also responsible for the product when it has been exported, thereby being required to provide mechanisms to improve the performance recovery rate of materials in destination countries (Li et al. (2013)). The key argument Thapa et al. (2023) used to support UPR is to acknowledge the global socio-economic inequalities and the ethical question of shifting waste or soon-to-be waste to another country with lower environmental standards and recycling and disposal capacities. According to the authors, circularity and sustainability in one location must consider global trade flows of new and used products, which should be incorporated through a longer-term perspective in a broader spatial context (Thapa et al., 2023). Following a similar argumentation, Torrente-Velásquez et al. (2020) conclude that local pollution in developing countries derived from the consumption of imported goods should be considered and included in EPR schemes, where the responsibility for the municipal solid waste derived from imported goods is extended beyond local boundaries, to the country of origin.

Should an international collaboration be established between Mongolia and Japan, or in the future between Mongolia and China, to enable the safe recycling of end-of-life batteries in the absence of domestic recycling capacity, the Basel Convention should not constitute a barrier to its implementation. Nevertheless, there must be



clear guidelines and inspections to guarantee that the batteries will be safely transported, recycled, and, if necessary, disposed of. With increasing material flows, establishing local recycling systems may be preferable to importing/exporting in the long term. Following the European Battery Passport example, the implementation of clear documentation of battery composition and design can support recycling initiatives and keep track of material flows in end-of-life batteries.

Even though it is widely recognized that both NiMH and LIB have the potential to be repurposed, reused, and recycled after their first life, it is key that the battery is adequately assessed to see which path it will be able to take. When looking into the benefits of reuse, expanding the lifespan of the batteries reduces the amount of new batteries and thus mitigates environmental damage caused by the extraction of raw materials. However, it must be kept in mind that reusing batteries is neither a trivial task nor a risk-free one (Rohr et al., 2017; Hua et al., 2021). It requires the creation of technical and supervisory capacities and can be best achieved by collaborating with local government, academic institutions, and industry (Hua et al., 2021).

Technology-wise, as suggested by Larsson et al. (2013), jointly pre-processing NiMH and Li-Ion batteries may be economically and practically preferable since it can support scaling up the process. Currently, Umicore already have systems to process both types of batteries (Valenzuela et al., 2024).

In addition, creating a culture of adequate and reliable data collection and registration is fundamental, including aspects related to vehicle imports, annual sales data, the characterization of vehicle fleets, waste generation, collection, and storage. Stakeholder engagement is crucial throughout the process to create knowledge and awareness. This could include adding waste quantification and characterization to Mongolia's material flow statistics.

6 Conclusion

In this study, the status quo of the transition to e-mobility and end-of-life battery management systems in Mongolia was investigated, aiming to support the development of strategies for a successful

transition to a circular economy regarding automotive battery management. When seen in a Resource Nexus perspective, the transition to electric mobility, when combined with the decarbonization of the electricity sector, has substantial climate benefits, but at the same time produces new challenges related to the disposal of EoL batteries, which may lead to the pollution of soil, water and the wider environment. Utilizing Material Flow Analysis (MFA) as the primary methodological approach, our findings indicate several key areas for improvement and strategic interventions that can enhance the efficiency and sustainability of Mongolia's waste management practices. Developments are required across all stages of the waste management chain, including collection, storage, reuse and recycling, and final disposal. This process involves developing better data collection and improving and reinforcing current waste management legislation.

The predictions showed that, in the Current Policy scenario, the quantity of EoL batteries generated in 2050 is estimated to be 4,261 tons of EoL LIB and 29 tons of EoL NiMH batteries. For the Climate Policies scenario, it is expected to be 11,841 tons of EoL LIB and 30 tons of NiMH EoL batteries. The very low values of NiMH in 2050 are due to the expected transition from NiMH to LIB in HEV. Cumulatively (from 2023 to 2050), in the Current Scenario, 10,302 tons of EoL NiMH and 38,650 tons of EoL LIB are generated, whereas for the Climate Focus Scenario, 10,455 tons of EoL NiMH and 102,586 tons of EoL LIB are expected.

Challenges appear when looking at the economic sustainability of reuse and recycling facilities in Mongolia since investments to implement recycling units are high, and there is no market for recovered materials in the country. Key recommendations to enhance the circularity of end-of-life automotive batteries in Mongolia are summarized below:

- *Focus on early stages of waste management:* Initially, the Mongolian government should prioritize improving the collection, storage, and reuse of EoL batteries.
- *Extended producer responsibility (EPR):* EPR is crucial for transitioning to a circular economy since it can be a tool to financially support the implementation of reverse logistics in Global South countries where governments have low investment

capacity. However, EPR needs to be adapted for international trade contexts, find innovative approaches to be applied across borders and support must be provided to prevent pollution and responsibility shifting from developed to developing countries.

- **Inclusion of informal sector:** Integrate informal waste pickers into the formal waste management system to enhance collection rates. This strategy brings social benefits for these workers by guaranteeing safer working conditions and better income.
- **Collaboration with repair shops:** Engage repair shops to support the collection and establishment of a reverse logistics system for end-of-life batteries. These stakeholders can support the environmental awareness of customers on how to properly dispose of EoL batteries.
- **Local solutions and technology:** Develop locally adapted solutions for reuse and recycling, and establish technical capacities through collaboration between government, academia, and industry. EPR schemes can be used to finance the development of such research projects.
- **Regional and international cooperation:** Explore regional or international solutions to upscale reuse and recycling systems, with clear responsibilities and improved Extended Producer Responsibility (EPR) schemes.
- **Data acquisition and stakeholder engagement:** Promote a continuous data acquisition and registration culture, and engage stakeholders to create knowledge and awareness throughout the waste management chain.

This research faced several challenges that are recurrent in studies involving emerging technologies such as LIB and data-scarce regions. Notably, the limited availability of accurate data on Mongolia's current vehicle fleet—such as annual sales figures, vehicle age distribution, and different vehicle models—introduces uncertainties in future projections. Additionally, the rapid pace of innovation in battery technologies and recycling processes contributes to uncertainty in the calculated outcomes.

These limitations are not unique to this study but reflect broader structural issues commonly encountered in Global countries, where data infrastructure and technical capacity are still evolving (World Bank, 2022). Further research is needed to better understand the role of repair shops and the dynamics of the informal sector, particularly in terms of their operational practices and technical requirements. Despite these challenges, the study underscores the importance of a collaborative approach—combining local and international expertise, technological innovation, and stakeholder engagement—to enhance the circularity and sustainability of end-of-life automotive battery management in Mongolia.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author/s.

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Author contributions

LP: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. GG: Investigation, Project administration, Supervision, Validation, Writing – review & editing. CD: Conceptualization, Supervision, Writing – review & editing, Methodology. DK: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, Data curation.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsus.2026.1664408/full#supplementary-material>

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