Supporting Information

Tracking Flows of End-of-Life Battery Materials and Manufacturing Scrap

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1. Materials-available-for-recycling model and key assumptions

Our materials-available-for-recycling model (created in Microsoft Excel™) is used to estimate the total quantity of material available for recycling, which is defined as the total material that is ready to be recycled in a given year. This total is equal to the sum of the following: materials available for recycling from end of first life (EOL_1), those reaching the end of their utility in reuse (reuse-to-recycle [R2R]), and those from production scrap. The steps in the model are shown in Figure S1.

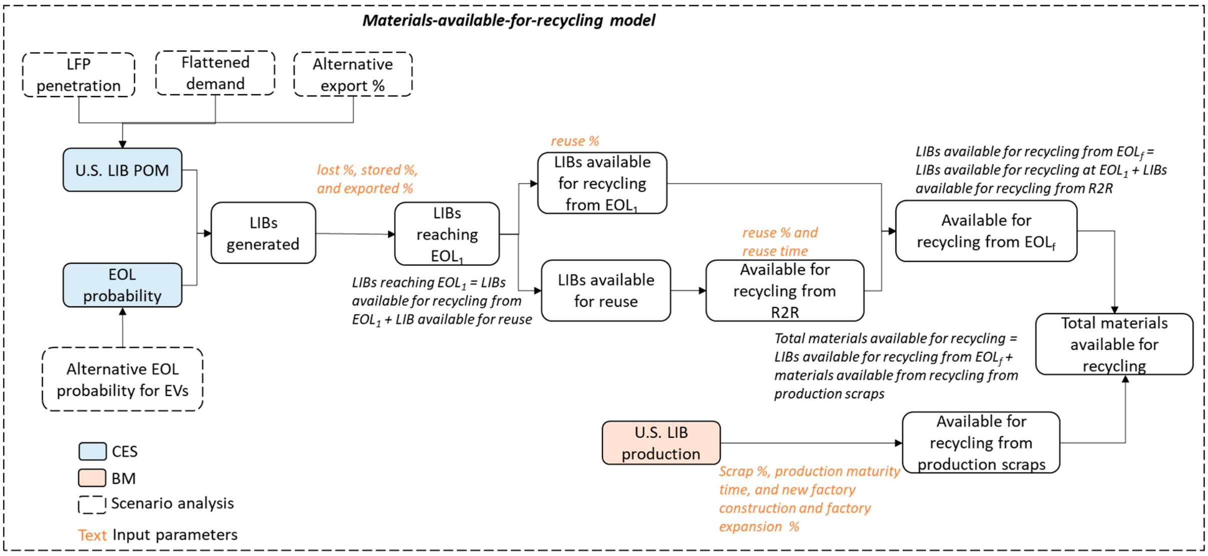


Figure S1. Materials-available-for-recycling model flow diagram (Sources: CES = Circular Energy Storage; BM = Benchmark Mineral Intelligence)

As shown in Figure S1, total material available for recycling is the sum of lithium-ion batteries (LIBs) available for recycling after all uses plus the material available from production scrap. LIBs available for recycling from final end of life (EOL_f) are, in turn, the sum of LIBs available for recycling after EOL_1 and those available for recycling after R2R. LIBs available for recycling from EOL_1 were defined as the total reaching EOL_1 minus those suitable for reuse. The total for LIBs available for recycling after R2R was estimated from LIBs reaching EOL_1, reuse rate, and reuse time. The total for LIBs reaching EOL_1 was further calculated from the quantity placed on the market (POM) by product type, the expected lifetime (EOL probability), and the rates lost, stored, and exported. The quantities for POM and EOL probability were obtained from Circular Energy Storage (CES) [33]. The main difference between our model and that of CES is the basis of the rate lost, stored, and exported. In our model, these rates are based on the quantity generated instead of those POM. In addition, we have added the R2R. The detailed definitions used to calculate LIBs available for recycling from EOL_f are listed below:

- **LIBs generated:** LIBs that have gone through their usage phase and reached EOL. In the model, stored %, lost %, and exported % are based on LIBs generated. The detailed calculation can be found in this supporting information (SI) Section 1.1.1.
- **LIBs reaching EOL_1:** LIBs generated minus those that were diverted by being stored, lost, or exported. This total consists only of LIBs available for recycling from EOL_1 and available for reuse. Detailed calculations can be found in SI Section 1.1.2.
- **LIBs available for recycling from end of first life (**EOL_1**):** LIBs available for recycling from the original hosts.
- **LIBs available from R2R:** LIBs available for recycling from LIBs reused in other applications or subsequent hosts. LIBs reused in the same host (resold) are counted as still in use.
- **LIBs available for recycling from end of final life (**EOL_f**):** The sum of LIBs available for recycling after end of first life (EOL_1) and LIBs from R2R.
- **EOL probability:** Lifespan probability distribution for different LIB applications.
- **Reuse rate (%):** Percentage of EOL LIBs judged available for reuse. Reuse diverts material and so reduces the percentage recycled immediately, but eventually the material can go to recycling.
- **Reuse time:** Length of service in second and subsequent lives.
- **Stored rate (%):** Mass percentage of (portable device) LIBs that would have been expected to go out of service at this time but are instead stored by the user and so counted as still in use.
- **Lost rate (%):** Mass percentage of (portable device) LIBs that would have been expected to go out of service at this time but are instead lost or discarded. EOL material is reduced by this material. The lost rate is expected to be negligible for electric vehicles (EV) and energy storage system (ESS) uses.
- **Export rate (%)**: Percentage of used LIBs (in or out of vehicles) that are sold outside the U.S.

Material available for recycling from production scrap was estimated from U.S. LIB production, scrap rate (%), production maturity time, and new factory construction and factory expansion rate (%). The U.S. LIB production data were obtained from Benchmark Mineral Intelligence (BM) [34], and detailed information can be found in SI Section 2. In this model, it is assumed that the scrap rate will decrease from 30% to 5% within the production maturity time T. However, factories learn from experience. If LIB demand is supplied by *new* factories, it takes T years for a factory to decrease its production scrap rate from 30% to 5%, but if LIB demand is supplied by factory *expansion*, it is assumed that the scrap rate is lowered to average past scrap rates due to previously gained experience. The main difference between this model and CES's model is the inclusion of a changing scrap rate with production maturity time and the learning capability for factory expansion. Definitions of the different terms can be found below, and the detailed model for estimating LIBs available for recycling from production scrap can be found in Section 1.2.

- **Scrap %:** Percentage of input material that is generated as scrap during cell production.
- **Production maturity time:** Years required for a factory to decrease production scrap from 30% to 5%.
- **New factory construction and factory expansion rate (%):** Increased capacity can be obtained either from new factory construction or factory expansion.
  New factory construction and factory expansion % = LIB production capacity increases from new factories/LIBs production capacity increases from factory expansion.
- **R2R:** LIBs that are recycled after fbeing reused in other applications or subsequent hosts.

1.1 LIBs available for recycling from EOL_f

1.1.1 LIBs generated

As mentioned in Section 1, "LIBs generated" is defined as LIBs that have completed their first usage life and reached EOL. The distribution of expected lifetimes, which we call the EOL probability for each application, was obtained from CES [1], and can be found in Figure 3 in the main article. The average lifespan for different applications used in the baseline scenario is shown in Table S1. An alternative scenario was examined to check the variation based on EV lifespan changes, given that EVs will dominate the market in the near future and that the lifespans of LIBs are likely to increase with technology advancement. In the model, LIBs generated is calculated based on the equation listed below:

$$LIB\ generated\ in\ year\ j = \sum_{x}^{all\ applications} \sum_{i=2000}^{n} POM_x\ in\ year\ i\ \times EOL\ probability\ for\ application\ x\ in\ year\ j\ (n<j) \quad \text{Eq. 1}$$

Table S1. Average lifespan used in the baseline scenario

	Portable devices	LEVs	HDEVs	ESS	Personal mobility	Industrial	UPS	Maritime
Baseline (years)	5	15	8	16	6	12	7	12

LEV = light-duty electric vehicle, HDEV = heavy-duty electric vehicle, ESS = energy storage system, UPS = uninterrupted power supply.

Table S2. Average lifespan used in the alternative scenario

Modeled average lifespan	2010–2014	2015–2019	2020–2024	2025–2029	2030–2034	2035–2040
LEV	10	12	15	16	18	21
HDEV	5	7	8	8	10	11

1.1.2 *LIBs reaching EOL_1*

LIBs reaching EOL_1 was calculated by subtracting the quantities stored, lost, and exported from LIBs generated. Test, reject, and unsold items were not counted due to lack of data. For simplification purposes, battery loss due to storage by users and improper disposal was only considered for portable devices due to the high value of EV and ESS LIBs, which will dominate the volumes in the future and are unlikely to be disposed of. Detailed assumptions for each parameter for the baseline scenario can be found in Table 4 in the manuscript. The total for LIBs reaching EOL_1 was calculated based on the equation below:

$$\begin{aligned} &LIB\ reaching\ EOL_1\ in\ year\ j \\ &= \sum_{x}^{all\ applications} \sum_{i=2000}^{n} (POM_x\ in\ year\ i\ \times EOL\ probability\ for\ application\ x\ in\ year\ j \\ &\times (1 - exported\ \%\ for\ application\ x\ in\ year\ j) \\ &- \sum_{i=2000}^{n} POM_{Portable\ Devices}\ in\ year\ i\ \times EOL\ probability\ for\ portable\ devices\ in\ year\ j \\ &\times (lost\ \%\ in\ year\ i + stored\ \%\ in\ year\ i)) \end{aligned}$$

Eq. 2

Export rate

Table S3 shows the export rate for portable devices, which was estimated from CES data [33], and for other products, from our own estimates. The lower and upper bounds were set to confirm that the export rates were not over- or underestimated. For the export rates of LEVs and HDEVs in Table S3, the average export rate value was based on that of conventional cars, which was calculated from the equation below. Results are shown in Table S4. The number of exported used cars was obtained from USITC [35], and the number of registered vehicles per year from the Experian auto registration database [36]. An alternative scenario was constructed to examine the effect of a high export rate, given that the export rate for used EVs could be as high as 30% based on the information obtained at the 2023 NAATBatt conference [37]. Detailed information on the scenario analysis can be found in SI Section 6.2.

The export rate of conventional cars in year i = the number of used cars exported in year i / the number of cars deregistered in year i.

$$\begin{aligned} &\#\ \text{of cars deregistered in year}\ i \\ &= \sum_{j=1967}^{i} (\#\ of\ cars\ registered\ with\ model\ year\ j\ in\ year\ i \\ &- \#\ of\ cars\ registered\ with\ model\ year\ j\ in\ year\ (i-1))\ (i > 1967) \end{aligned}$$

Eq. 3

Table S3. Assumed exported rates for LIBs in different applications

Exported rate	Average	Lower bound	Upper bound
Portable devices (such as smartphone, laptops, and chargers)	45% (2000–2019); 20% (2020–2024); 10% (2025–2040)	30% (2000–2019); 10% (2020–2024); 5% (2025–2040)	60% (2000–2019); 30% (2020–2024); 15% (2025–2040)
LEV	**5%** (30%)	3%	10%
HDV	**5%** (30%)	3%	10%
Other batteries	10%	5%	20%

Table S4. Estimated exported rates of conventional cars in different years

	Number of exported used cars	Estimated deregistered cars	Exported rates
Year 2014	6.7E+05	1.0E+07	6.61%
Year 2015	5.2E+05	1.1E+07	4.58%
Year 2016	5.1E+05	1.1E+07	4.63%
Year 2017	5.9E+05	1.2E+07	4.82%
Year 2018	7.4E+05	1.2E+07	6.38%

1.1.3 *LIBs available for recycling after end of final life (EOL_f)*

LIBs available for recycling after EOL_f is the sum of LIBs available for recycling from EOL_1 and LIBs from R2R. The quantity available for recycling in a particular year was estimated from Equation 4 below. Reuse time and reuse rate are shown in Table S5. The lower and upper bounds will be discussed further in SI Section 9.

$$LIBs\ available\ for\ recycling\ from\ EOL_f\ in\ year\ j = \sum_{x}^{all\ applications} (LIBs\ reaching\ EOL_1\ for\ application\ x\ in\ year\ j\ \times (1 - reuse\ \%\ for\ application\ x) + LIBs\ reaching\ EOL_1\ for\ application\ x\ in\ year\ (j-m) \times\ reuse\ \%\ for\ application\ x) \qquad \text{Eq. 4}$$

where m = reuse time.

Table S5. Reuse rate and reuse time of different LIB chemistries in different applications [38, 39]

Applications	Chemistries	Period	Baseline	Lower bound	Upper bound	Baseline	Lower bound	Upper bound
LEV	LFP	2000–2019	85%	75%	95%	6	4	8
		2020–2050	90%	80%	95%	6	4	8
	Other chemistries	2000–2019	60%	50%	70%	6	4	8
		2020–2050	70%	60%	80%	6	4	8

HDV	LFP	2010–2019	70%	60%	80%	6	4	8
		2020–2050	75%	65%	85%	6	4	8
	NMC622	2010–2050	80%	75%	85%	6	4	8
	Other chemistries	2010–2050	80%	75%	85%	6	4	8
Portable electronics			20%	10%	30%	2	1	3
Personal mobility			30%	20%	40%	2	1	3
Industrial	LFP		70%	40%	90%	4	2	6
ESS			55%	40%	70%	6	4	8
UPS	LFP	2017–2050	70%	50%	90%	2	1	3
Maritime	LFP	2019–2020	70%	50%	90%	6	4	8

NMC = Nickel manganese cobalt.

1.1.4 *Li, Co, and Ni that can be recovered from EOL_f*

The elements that can be recovered from EOL_f were estimated from the chemistry mix of LIBs available for recycling (calculated in Section 1.1.3) and the percentages of Li, Co, and Ni they contain, as shown in Table S6. The detailed calculation equation is shown below. Note that this equation calculates the maximum values, because the recycling process efficiency is set to 100% to calculate the maximum recovery. Recycling process efficiency is defined as the mass of recycled materials exiting the recycling process and returned to the economy divided by the mass of materials entering the recycling process (expressed as a percent).

$$Element\ that\ can\ be\ recovered\ from\ EOL_f = \sum_{y}^{All\ chemistries} LIBs\ available\ for\ recycling\ for\ chemistry\ y\ from\ EOL_f \times \%\ of\ element\ contained\ in\ spent\ LIB\ for\ chemistry\ y \quad \text{Eq. 5}$$

Table S6. Mass percentage of Li, Co, and Ni contained in spent LIBs by chemistry [8]

	LCO	NMC111	NMC532	NMC622	NMC721	NMC811	NCA	LMO_x	LFP	LMO
Li	2.60%	2.87%	2.86%	2.65%	2.65%	2.32%	2.52%	2.02%	1.78%	2.02%
Co	21.28%	7.91%	4.73%	4.38%	2.19%	1.90%	3.12%	0.00%	0.00%	0.00%
Ni	0.00%	7.87%	11.79%	13.08%	15.26%	15.18%	16.55%	0.00%	0.00%	0.00%

LCO = Lithium cobalt oxide, NMC = Nickel manganese cobalt, LMO = lithium ion manganese oxide, LFP = lithium iron phosphate.

1.2 Materials available for recycling from production scrap

We assume that an increase in LIB production capacity results from either a capacity expansion in existing factories or new facilities being built. To simulate the real condition, it is assumed that for factory expansion, the scrap rate is equal to the average rate from past years due to the experience gained. For new factories, the scrap rate is assumed to decrease from 30% to 5% with the maturity of the technology, as shown in Table S7. Three production maturity times were considered in this study: The baseline scenario has a production maturity time of four years, and a faster production maturity time of two years, and a slower production maturity time of six years are also considered [40]. The split between new factory construction and factory expansion was estimated based on the LIB production increase rate. In 2010, it was assumed that all LIB production was from new factories since the U.S. had just started LIB production. If the LIB production increase rate (LIB production in year *i*/LIB production in year *i*-1) is more than or equal to 1.8, it is assumed that 50% of LIB production increase is from new factories, and the rest is from factory expansion. If the production increase rate is less than 1.8, it is assumed that 80% of LIB production increase is from factory expansion, and the rest is from new factories. This dividing line is set to be 1.8 based on observation of the LIB production increase trend.

To examine upper and lower bounds of LIBs available for recycling from the quantities of production scrap, we considered two conditions: All production capacity increase is from only new factories and capacity increase is attributable only to factory expansion after 2010. Detailed results can be found in Section 3.2.

Table S7. Scrap rate by years

Scrap rate by years	1	2	3	4	5	6
4-year scenario	30%	22%	13%	5%		
2-year scenario	30%	5%				
6-year scenario	30%	25%	20%	15%	10%	5%

1.2.1 Li, Co, and Ni that can be recovered from production scrap

Elements that can be recovered from production scrap were estimated from production scrap volume by chemistry and by the percentages of Li, Co, and Ni contained in the production scrap. Scrap breakdown chemistry was estimated using Equation 6, and elements recoverable from production scrap from Equation 7. These are the maximum values because the recycling process efficiency is presumed to be 100%. Scrap rates were calculated from cell acceptance yield after testing and material yield per cell, obtained from BatPac [8], and the values are listed in Table S8. The calculated Li, Co, and Ni contained in production scrap by chemistry are shown in Table S9.

Manufacturing scrap breakdown = (1/cell acceptance yield/material yield – 1/cell acceptance yield) × cell material composition.

Eq. 6

$$Elements\ that\ can\ be\ recovered\ from\ production\ scraps = \sum_{y}^{All\ chemistries} Materials\ available\ for\ recycling\ for\ chemistry\ y\ from\ production\ scraps \times \%\ of\ element\ contained\ in\ production\ scraps\ for\ chemistry\ y$$

Eq. 7

Table S8. Cell acceptance yield (%) and material yield (%) [8]

Cell accepted after testing	95%					
Material yield per cell						
	Overall	**Mixing**	**Coating**	**Electrode slitting**	**Cell stacking**	**Electrolyte filling**
Active cathode material	92.2%	99%	95%	99%	99%	
Active anode material	92.2%	99%	95%	99%	99%	
Aluminum foil	90.2%		99%	92%	99%	
Copper foil	90.2%		99%	92%	99%	
Separator	98.0%				98%	
Electrolyte	99.0%					99%

Table S9. Mass percentage of Li, Co, and Ni contained in production scrap by chemistries

	LCO	**NMC111**	**NMC532**	**NMC622**	**NMC721**	**NMC811**	**NCA**	**LMO_x**	**LFP**	**LMO**
Li	2.8%	3.0%	2.9%	2.7%	2.7%	2.4%	2.6%	2.1%	1.9%	2.1%
Co	23.1%	8.2%	4.9%	4.5%	2.3%	2.0%	3.2%	0.0%	0.0%	0.0%
Ni	0.0%	8.2%	12.2%	13.6%	15.8%	15.8%	17.2%	0.0%	0.0%	0.0%

LCO = Lithium cobalt oxide, NMC = Nickel manganese cobalt, LMO = lithium ion manganese oxide, LFP = lithium iron phosphate.

2. Data sources

Table S10 provides an overview of the data sources used for various input parameters. LIB POM, EOL probability, reuse %, and reuse time were obtained from CES. In addition, export %, stored %, lost %, scrap %, production maturity time, and new factory construction and factory expansion % were estimated based on literature and experience in this study.

Table S10. Summary of input parameters data sources

Parameters	Data sources	Notes
U.S. LIB POM	CES ([35])	The data were projected from volume data and indicators (see Tables S11 and S12)
EOL probability	CES ([37])	Lifetime expectancy of EV batteries, portable batteries, and other batteries were estimated from indicators (see Table S12).

Exported %	This work ([33], [32-37])	Please see details in section 1.1.2
Stored % and lost %	This work	Table 4 in the manuscript
Reuse % and reuse time	CES and literature ([38] and [39])	The data were projected from indicators (see Table S12)
U.S. LIB production	BM ([33] and [34])	
Scrap %, production maturity time, and new factory construction and factory expansion %	This work ([39])	Please see details in section 1.2

CES = Circular Energy Storage; BM = Benchmark Mineral Intelligence

The data obtained from CES are based on information in two different categories: volume data and indicators. More detailed information can be found in the two Tables below.

Table S11. Sources of volume data

Category	**Subcategory**	**Data sources of volume data**	**Data sources of battery data (weights, chemistries, formats)**	**Data granularity**
Portable batteries	• Cameras and camcorders • Mobile phones • Laptops • Tablets • Power and garden tools • Power banks • Other portable batteries	• Industry analysts (Gartner Group for main categories) • Industry associations, financial reports from industry leaders	• Data sheets from manufacturers • Open source information • Conducted disassembly of battery packs	Cell data averages applied to regional deliveries of applications + estimates of replacement frequency
Personal mobility batteries	• E-bikes • E-scooters and motorcycles • Electric three-wheelers, skateboards and other mobility devices	• Industry associations • Financial reports from industry leaders • Iindustry media	• Data sheets from manufacturers • Open source information • Conducted disassembly of battery packs	Cell data averages applied to regional deliveries of applications + estimates of replacement frequency

	• Wheelchairs and mobility scooters			
Light EV batteries	• BEV and PHEV up to 2 tonnes • BEV/PHEV over 2 tonnes mainly for private use	• Primary data from national and state vehicle registration agencies • Financial reports from vehicle manufacturers • EV user groups on social media (for battery replacement frequency)	• Announcements and direct communication with vehicle manufacturers • Media reports, refurbishes and car dismantlers	Cell data for each vehicle model applied to country and regional level
Heavy and commercial EV batteries	• Hybrid and trolley buses, electric buses • Electric vans and commercial pickups • Electric and hybrid light trucks • Electric medium and heavy trucks	• Primary data from national and state vehicle registration agencies • Financial reports from vehicle manufacturers • Warranty policies from OEMs (for replacement frequency)	• Announcements and direct communication with vehicle manufacturers • Media reports • Refurbishers and car dismantlers	Cell data for each vehicle model applied to country and regional level, as well as estimates for some vehicle categories
Stationary energy storage systems	• Utility scale energy storage systems • Commercial and industrial energy storage systems • Residential energy storage systems • Energy storage systems for EV charging	• Industry analysts (Bloomberg NEF, Wood Mackenzie) • Industry associations, financial reports • Listed ESS companies, Media reports	• Announcements and direct communication with ESS and battery manufacturers • Media reports	Regional deployments based on other analysts' assessments in combination with estimates of cell types
Industrial batteries	• Forklifts • Robots • Medical equipment • Utility vehicles • Leisure batteries • Mobile power packs	• Industry associations • Financial reports from industry leaders • Industry media	• Announcements and direct communication with equipment and battery manufacturers • Media reports	Regional deployments based on industry associations in combination with estimates of cell types

Backup batteries	• UPS for telecom basestations • Data centres and industrial facilities	• Industry associations, financial reports from industry leaders • Industry media	• Announcements from UPS and backup system providers • Media reports	Regional deployments based on industry associations in combination with estimates of cell types
Maritime batteries	• Batteries in ferries • Hybrid freight vessels • Maritime power packs Small boats	• Industry associations • Financial reports from industry leaders • Industry media	• Announcements from vessel and battery manufacturers • Trade associations, Media reports	Regional deployments based on industry associations in combination with estimates of cell types
Automotive batteries	• SLI batteries	• Announcements from manufacturers of SLI batteries • Announcements from car makers, media reports	• Announcements from battery manufacturers	Cell data averages applied to regional vehicle sales

Table S12. Data sources for indicators

Indicator category	**Indicators**	**Main sources**	**Updating frequency**
Future growth rate of EV batteries for individual models	• Regional and national sales of similar ICE vehicles • Earlier sales trajectories of EVs in countries with higher EV penetration • Subsidy structure and price comparisons with ICE vehicles • Vehicle and battery makers' markets shares • Current delivery times of vehicles	• Industry associations and national vehicle registration authorities • Government information • Media reports	Once a year
Future growth rate of other applications	• Growth rates according to industry analysts of total application market (including applications with other types of batteries or other types of power sources) • Penetration rates of lithium-ion batteries in specific applications	• Industry associations • Ffinancial reports from industry leaders • Industry media	Once a year

Lifetime expectancy EV batteries	• Stock of individual EV models by country • Prices of used EVs in original countries • Mileage of used EVs in both original and import countries • Frequency of battery replacements • Prices and frequency of EV batteries at car dismantlers • Fault ratios of certain battery types • Battery lifetime models	• National vehicle registration authorities (verifying stock in both export and import countries) • Used car sales web sites in both export and import countries • Participation in EV user groups on social media (understanding battery replacement frequency, typical problems etc.) • Discussions with refurbishment and remanufacturing companies • Academic and commercial research on battery cycling, SOH and battery behavior	Continuously, at least once a year
Lifetime expectancy of portable batteries	• Prices of used portable electronics • Replacement frequency • Age frequency at battery collectors • Age frequency of devices at e-waste processors and ITADs	• Trading platforms for used electronics • Personal communication with battery, e-waste, ITAD and used electronics traders • Age assessments together with battery sorters and collectors	Occasionally
Lifetime expectancy of other batteries	• Replacement frequency • Warranties from manufacturers	• Product information from leading manufacturers • Publicly available RFQs	Occasionally
Reuse ratio	• Prices of used batteries • Prices of new batteries • Deployments of used batteries • Market size and growth of reuse segments • Quality assessments of retired batteries	• Trading platforms for car dismantlers and automotive spare parts • Collection of offers from battery manufacturers and traders • Collection of prices from retailers and whole sales of used batteries • Personal communication with battery reuse companies and their customers • Media reports and press releases from players in the market • Collaboration with battery sorters and collectors	Continuously (deployments and market), quarterly (prices)

Recycling ratio	• Prices of scrap battery cells • Prices of black mass • Prices of battery materials • Reported volumes by recyclers • Available capacity • Historical, current and future legislation and policy	• Direct communication with recyclers, collectors and battery owners • Price assessment agencies • Media reports • Statistics from collection organisations • Financial reports from listed recyclers and material companies	Monthly

The U.S. LIB production from 2010 to 2014 was estimated from production scrap data obtained from CES (LIB production = production scrap/0.1) [33]. Estimates of U.S. LIB production data for EVs and ESS from 2015 to 2030 were obtained from BM [34]. The detailed U.S. POM and production estimation can be found in Table S13, and the comparison of U.S. LIB POM to U.S. LIB production is shown in Figure S2.

Table S13. Estimation of U.S. LIBs POM and production*

Years	U.S. POM (tonnes)	U.S. production (tonnes)
2010	33,958	99
2011	37,600	571
2012	50,713	1,171
2013	68,934	1,971
2014	71,612	2,871
2015	82,231	3,871
2016	95,122	4,947
2017	114,844	27,960
2018	166,014	117,001
2019	180,953	132,271
2020	195,078	143,885
2021	301,723	172,275
2022	451,562	201,310
2023	622,910	253,006
2024	776,764	346,340
2025	944,791	606,297
2026	1,136,536	892,132
2027	1,354,695	1,332,993
2028	1,607,269	1,752,734
2029	1,918,258	2,069,109
2030	2,306,880	2,269,043

Blue = Data obtained from CES.

Pink = Data obtained from BM.
Green = The research team's own estimation.
*U.S. LIB production (tonne) = U.S. LIB production (MWh) × weighted average conversion factor for LIBs.
Weighted average conversion factor for LIBs (ton/MWh) = 4.3.

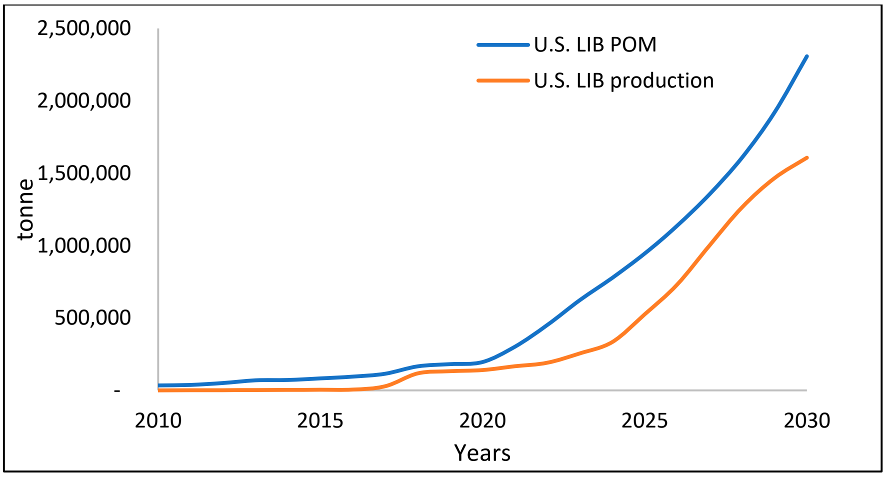


Figure S2. U.S. LIB POM and LIB production

3. Results

3.1 Lithium-ion batteries available for recycling from EOL_f

LIBs available for recycling from EOL_f include LIBs available from EOL_1 and LIBs available from R2R. Figure S3 shows the estimates of LIBs available for recycling from EOL_f by applications for the baseline scenario. Note that from 2000 to 2030, the majority of LIBs available for recycling from EOL_f are from portable devices, as portable devices dominated U.S. POM before 2016 and few long-lived EVs reach EOL_f during the period.

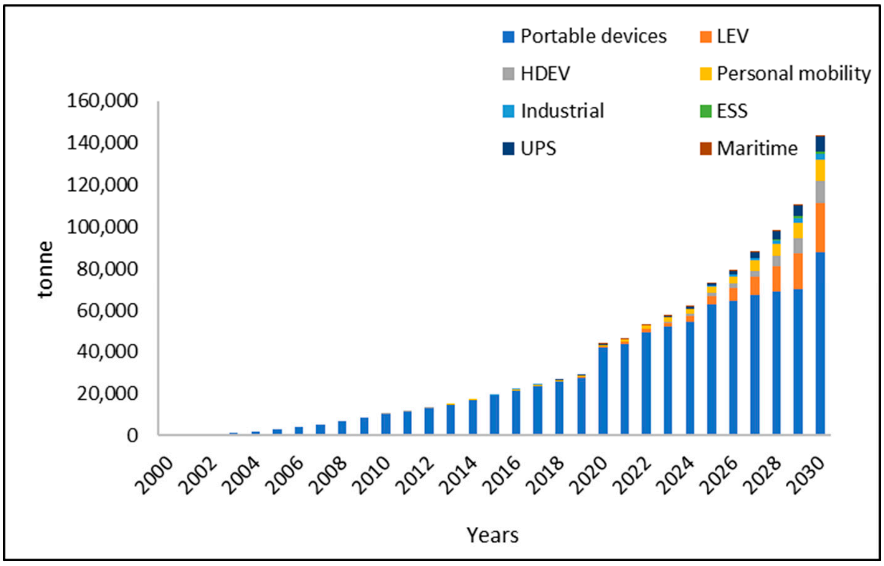


Figure S3. LIBs available for recycling from EOL_f by applications for the baseline scenario

3.1.1 Li, Co, and Ni that can be recovered from EOL_f

Li, Co, and Ni that can be recovered from EOL_f from 2000 to 2030 were calculated based on the methods shown in Section 1.1.4, and the results and lower and upper bounds based on different input parameters shown in Tables S17 and S18 are shown in Figure S4.

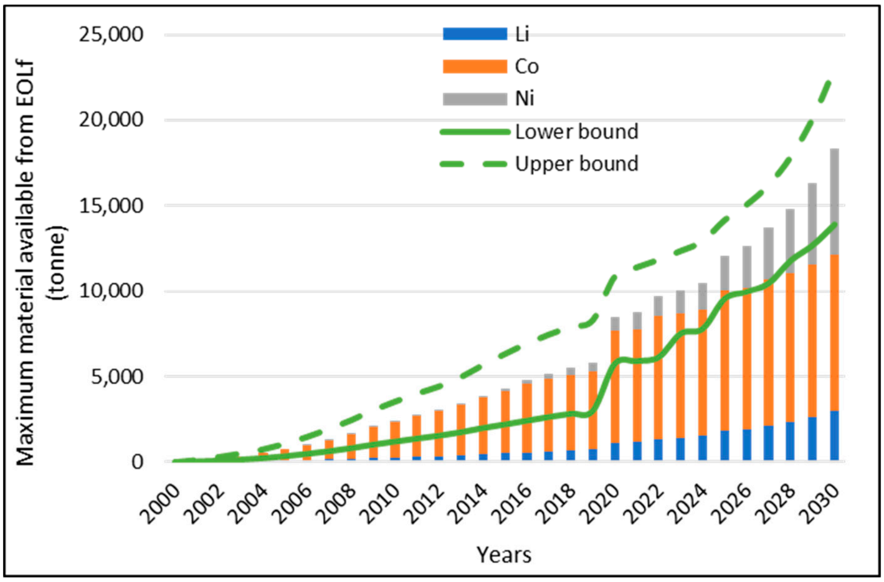


Figure S4. Li, Co, and Ni that can be recovered from EOL_f in the baseline scenario and lower and upper bounds

3.1.2 Percentages of Li, Co, and Ni contained in U.S. POM that can be satisfied by recycling (from EOL_f)

Figure S5 shows the percentage of elements in POM materials that can be satisfied by recycling from EOL_f for the baseline scenario, for which the assumptions are defined in Table 4 in the manuscript. The percentages are lower than those shown in Figure 12 in the main body of the article because Figure 12 shows the percentage of elements contained in POM that can be satisfied by LIBs generated, which is the upper bound of materials that can be recovered.

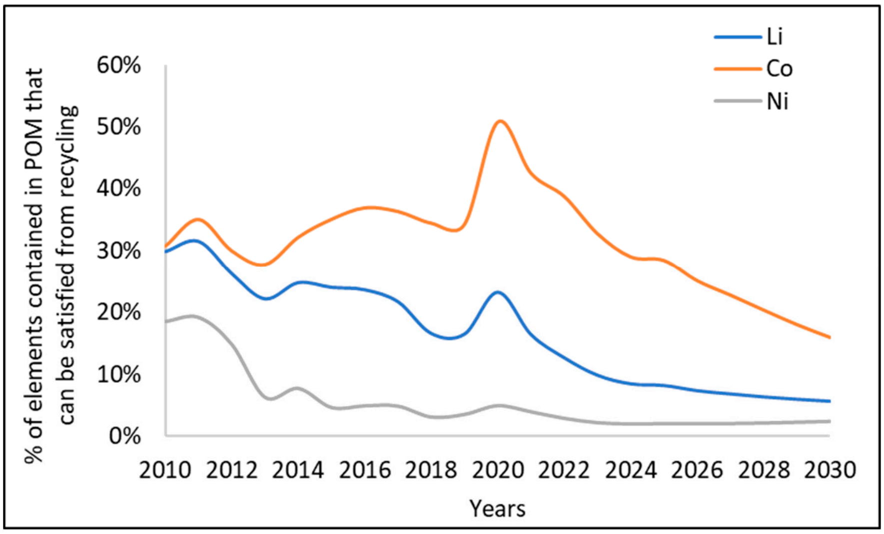


Figure S5. Percentage of Li, Co, and Ni contained in POM that can be satisfied by recycling (from EOL_f) for the baseline scenario

3.2 Materials available for recycling from production scrap

Figure S6 shows the baseline scenario (four years production maturity time), and two alternative scenarios for production scrap (of two years and six years to production maturity time). The upper and lower bounds show the extreme cases when all LIB production capacity increase occurs only in new factories and from factory expansion.

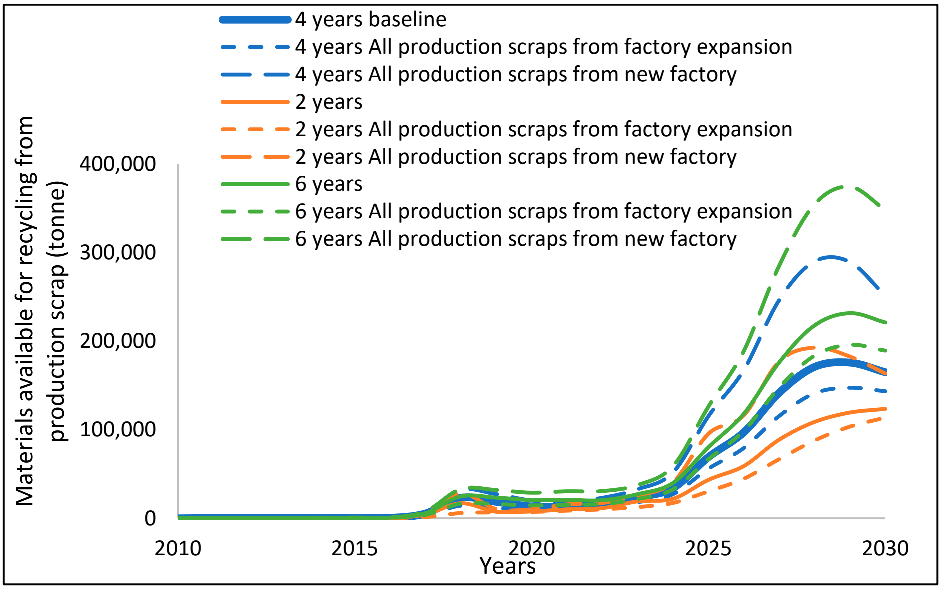


Figure S6. Materials available for recycling from production scrap with different production maturity times and new factory construction and factory expansion %

4. Pretreatment and recovery capacity in North America

Tables S14 and S15 show confirmed recovery plants and pretreatment-only plants in North America, respectively.

Table S14. Confirmed North American recovery plants (capacities are in metric tonne)

Company	Location	2023 Capacity (T/y)	Planned (T/y)	Recovery Method	References
ACE	Texas	0	1,800	hydro	[41]
American Battery Technology	Nevada	20,000	50,000	hydro	[42]
Ascend Elements	Georgia	30,000	30,000	hydro	[43]
Ascend Elements[2]	Kentucky	0	20,000[1]	cathode from precursor	[43]
Cirba Solutions[2]	Arizona	0	10,000	hydro	[37]
Cirba Solutions	South Carolina	0	10,000	hydro	[44]
Electra Battery Materials	Quebec	75	4,300	hydro	[45]
Glencore[2]	Ontario	~10,000	~10,000	pyro	[33]
Li-Cycle[2]	New York	0	35,000	hydro	[46]
OnTo Technologies	Oregon	1.8	1.8	direct	[47]
Princeton NuEnergy	Texas	500		direct plasma	[48, 49]
Princeton NuEnergy	TBD		3,000		[50]
Recyclico	British Columbia	180	60,000	hydro	[48, 49]
Redwood Materials	Nevada	250	20,000	hydro	[33, 37, 51]
REelement	Indiana	56	95,000	chromatography	[52]
Total recovery capacity		**61,063**	**329, 102**		

[1] Input is cathode precursor and it is from Ascent Elements in GA (Total recovery does not include the capacity of Ascend Elements in Kentucky to avoid double counting).

[2] Not assumed to have preprocessing capacity.

Table S15. Confirmed pretreatment-only plants (capacities are in metric tonne)

Company	Location	2023 Capacity (T/y)	Planned (T/y)
Blue Whale	TBD	0	14,000
Cirba Solutions	Arizona	0	10,000
Cirba Solutions[3]	Ohio	2,000	2,000
Cirba Solutions	British Columbia	2,000	2,000
Li-Cycle	Alabama	10,000	10,000
Li-Cycle	Arizona	10,000	10,000
Li-Cycle	New York	5,000	5,000
Li-Cycle	Ontario	5,000	10,000
Lithion	Quebec	7,500[4]	7,500
RSR/EcoBat	Texas	500	-
Recycling Coordinators	Ohio	5,000	-
Spiers New Technology	Oklahoma	-	-
Total pretreatment only capacity		47,000	70,500

[3] Formerly Battery Solutions

[4] August–September 2023 [48]

5. Sensitivity analysis

There are uncertainties for each input parameter, and sensitivity analyses were conducted to evaluate how our results varied for changes of input parameters of +/-20%. Note that the export rate has large uncertainties due to a lack of data, and two ranges, +/-20% and +/-50%, were selected to examine its impact (Figure S7). We separated the sensitivity analysis into two parts because we used two different data sources.

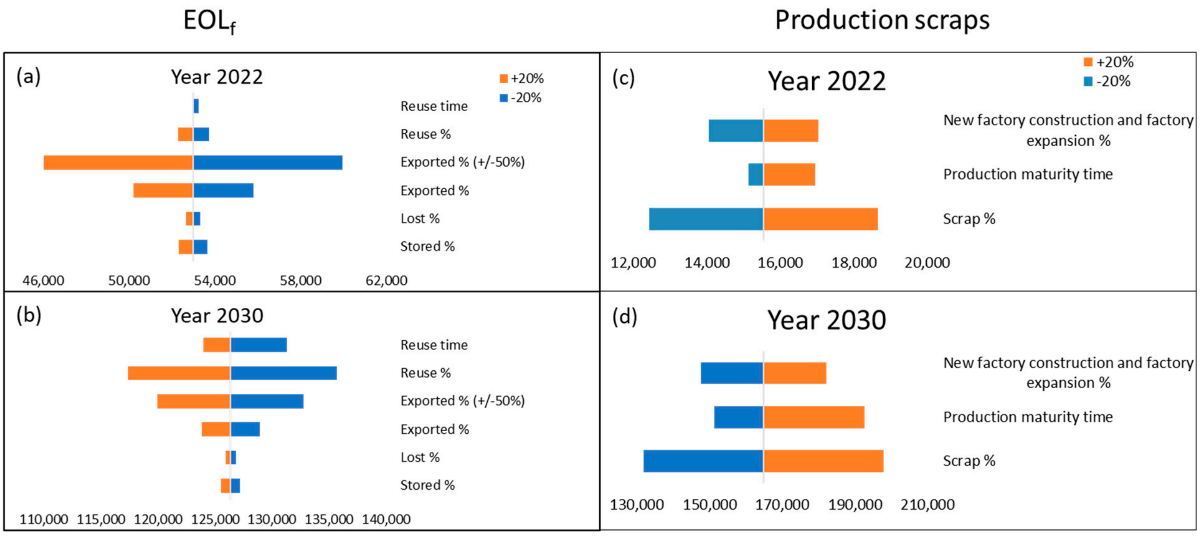


Figure S7. (a) and (b) sensitivity analysis of LIBs available for recycling from EOL$_f$ in year 2022 and year 2030; (c) and (d) sensitivity analysis of materials available for recycling from production scrap in year 2022 and year 2030

As shown in Figure S7 (a) and (b), the export rate has the largest impact on LIBs available for recycling from EOL$_f$ in 2022, whether the export rate variation is based on +/20% or +/-50%. In 2022, the large impact of the export rate can be explained by portable devices, which have a relatively high export rate before 2025 and constitute 93.6% of LIBs available for recycling from EOL$_f$, due to the long lifespan of EVs. In 2030, the impacts from export rate decrease, and impacts from reuse rate and reuse time increase. One of the reasons for that is that EVs become a higher percentage of LIBs available for recycling from EOL$_f$, and LIBs used in EVs have relatively high reuse rate values. Specifically, in 2030, light-duty EVs and heavy-duty EVs are estimated to constitute 26.6% of LIBs available for recycling from EOL$_f$, and EVs have relatively high reuse rates (60–90%). Other batteries, including ESS, marine, industrial, and uninterruptible power supply (UPS) batteries, make up about 6.2%, and LIBs from these applications also have relatively high reuse rates. It is expected that the impacts from reuse rate and reuse time will still be the dominant impact factors after 2030, because retired EV LIBs will constitute a higher percentage of LIBs available due to a stable portable devices market and a rapidly increasing EV market. Another reason for the increasing importance of reuse rate and reuse time and the decreasing importance of export rate is that the export rate of portable devices is assumed to decrease over the years in our model. The export rate of portable devices decreases from 20% to 10% from 2025 to simulate the real export condition of portable devices. As a result, the variance based on the change of export rate is not as sensitive as before.

As shown in Figures S7 (c) and (d), the scrap rate has a larger impact on materials available for recycling from production scrap than the production maturity time(s) or the new factory construction and factory expansion rates. The U.S. did not have substantial LIB production capacity until 2015, and during this period most LIBs were produced from new factories, which have relatively high scrap rates compared to expanded factories. With technology advancement, factories produce LIBs more efficiently because they can learn from experience, so the influence of the scrap rate decreases over time.

6. Scenario analysis

Five different scenarios are used in this study to examine the variation of LIBs available for recycling:

- Alternative lifespan scenario: Changing lifespan of LEVs and HDEVs (a detailed description of this scenario can be found in Section 1.1.1).
- A 30% export rate for EVs scenario: Baseline scenario assumes the export rate for EVs is about 5% each year; however, according to different sources, export rate can reach as high as 30%.
- Upper bound scenario: In this scenario, we examine how much material can be kept in the U.S. if there are no exports, losses, or disposal.
- LFP penetration scenario: Although different LFP penetration scenarios have been considered, only if LFP takes up 80% of market share after 2024 can it have a real impact on LIBs available for recycling. Scenarios with slower penetration were examined but are not discussed here.
- Flattened demand scenario: In this scenario, we examine the change of % of element contained in POM that can be satisfied by recycling when the POM is flattened.

6.1 Alternative lifespan scenario

It is assumed that the lifespan of LEVs and HDEVs will change every five years (a detailed description of this scenario can be found in Section 1.1.1). As shown in Figure S8, the changing lifespan of EVs will not have significant impacts on LIBs generated, which indicates that the increase of lifespan with technology advancement will delay the LIBs available for recycling, but the amount is not significant.

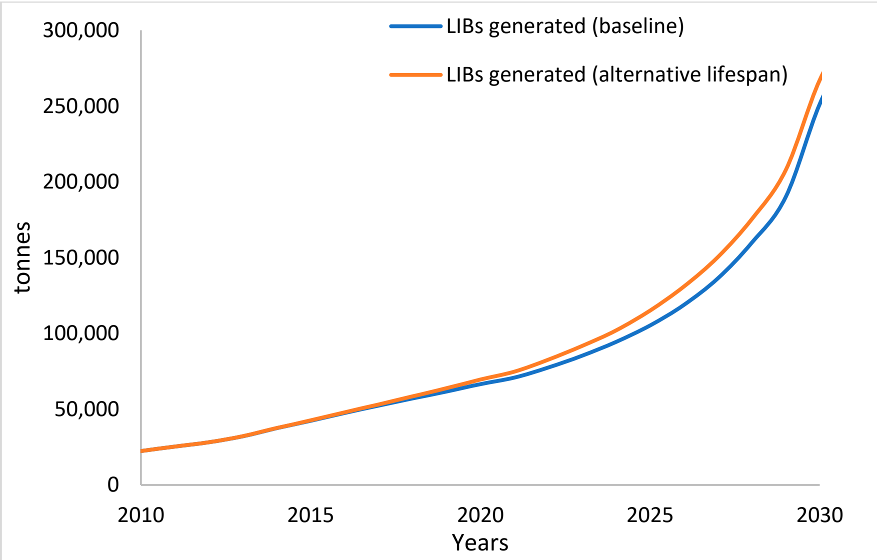


Figure S8. Comparison of LIBs generated between the baseline and alternative lifespan scenarios

6.2 The 30% export rate for EVs scenario

The export rate for EVs has relatively large uncertainties due to a lack of data. One participant at the 2023 NAATBatt conference [37] claimed a 30% exported rate for used LIBs, much higher than the baseline exported rate of 5%. As a result, a scenario with a 30% export rate was evaluated to check the impact of different export rates. As shown in Figure S9, a 30% export rate would decrease the quantity of materials that could be recovered in the U.S. because more materials will be exported to other countries. As more EVs with LIBs are retired, the export rate will play an important role in material recovery. The increase of export rate from 5% to 30% would decrease LIBs available for recycling from EOL_f in LEVs and HDEVs by a total of 26.3%.

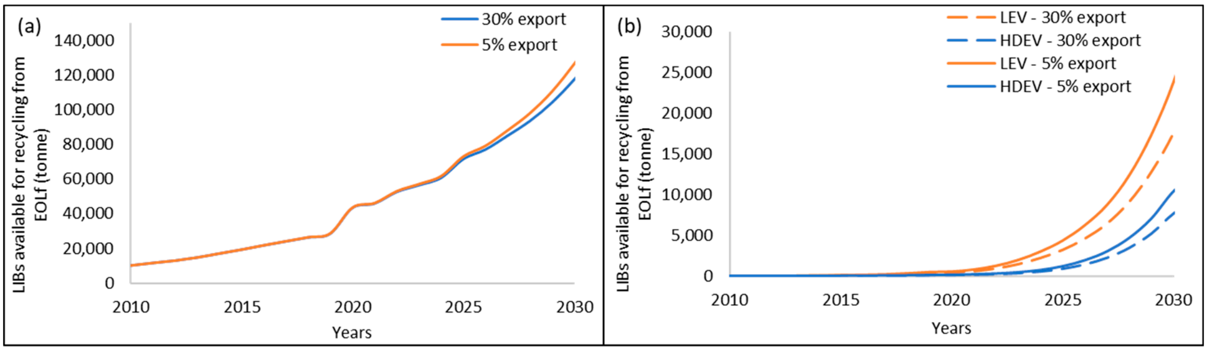


Figure S9 (a) Comparison between LIBs available for recycling with 5% and 30% export rates for EVs; (b) comparison between LIBs available for recycling for LEVs and HDEVs with 5% and 30% export rates for LEVs and HDEVs

6.3 Upper bound scenario

In this scenario, we examine the upper bound of materials that can be recovered domestically if no batteries are exported, disposed of in landfills, or stored by users. The percentage of POM elements that can be satisfied by recycling (from EOL_f) without exports, loss, or disposal were compare with those from the baseline scenario, and the results are shown in Figure S10.

Figure S10. (a), (b), and (c): Percentages of Li, Co, and Ni contained in U.S. POM that can be satisfied by recycling in a scenario without export, loss, or storage; (d), (e), and (f): Percentage of Li, Co, and Ni contained in U.S. POM that can be satisfied by recycling in a scenario with export, loss, and storage

6.4 LFP penetration scenario

As mentioned previously, different LFP penetration scenarios were considered in this study:

S1: LFP in LEVs and HDEVs is expected to increase by 50%, and the increase will be offset by a corresponding decrease in the utilization of NMC822.

S2: LFP in LEVs and HDEVs is expected to increase by 100%, and the increase will be offset by a corresponding decrease in the utilization of NMC822.

S3: LFP in LEVs and HDEVs is expected to decrease by 50%, and the decrease will be offset by a corresponding increase in the utilization of NMC822.

S4: LFP is expected to take up 80% of U.S. EV LIB POM from 2025.

From the calculation, only S4 has significant impacts on materials that can be recovered from EOL_f. Figure S11 shows that the change of LIBs' dominant chemistry from NMC to LFP will significantly increase the percentage of Ni and Co contained in POM that can be satisfied by recycling from EOL_f.

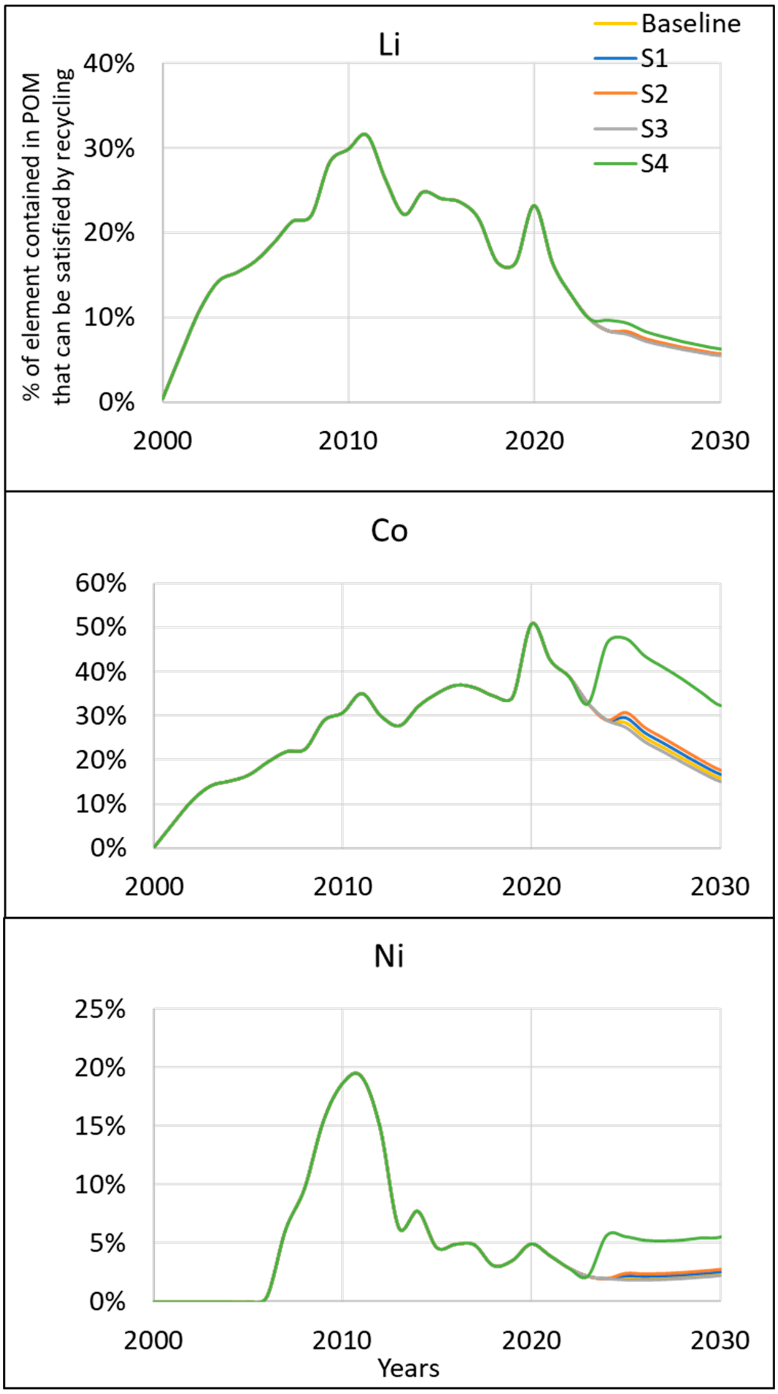


Figure S11. Percentage of elements in POM that can be satisfied by recycling (from EOL_f) in different LFP penetration scenarios

6.5 Flattened demand scenario

This scenario assumes that U.S. LIB POM is flattened after 2023. The change in percentages of each element contained in POM that can be satisfied by recycling is shown in Figure S12. If there is no increasing demand after 2023, the percentage of elements demanded that can be satisfied by recycling will increase significantly after 2023. Although this scenario may not be realistic, it shows how the percentage of demand that could be satisfied by recycling could change after the demand is flattened.

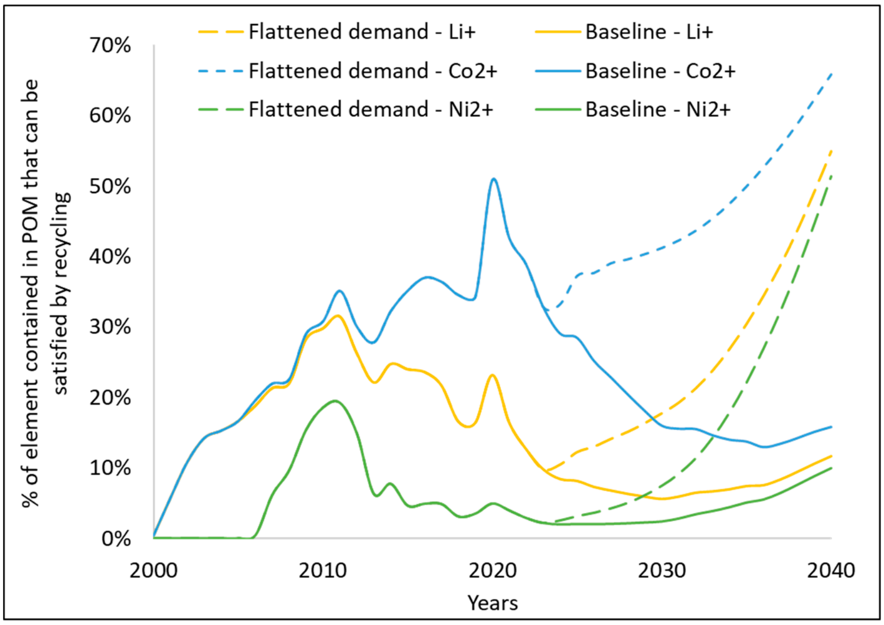


Figure S12. Percentage of element contained in POM that can be satisfied by recycling when U.S. LIB POM is flattened after 2023

7. Validation of the data with data from CES

We compared LIBs reaching EOL_1 from our model with projections from CES, and the comparison is illustrated in Figure S13. The differences are mainly attributable to the difference assumed for stored, lost, and exported rates in our model and the inclusion of LIBs available for recycling from R2R. Note that LIBs available for recycling from CES is defined as LIBs available for recycling from $EOL_{1,}$ since R2R is excluded from the CES model.

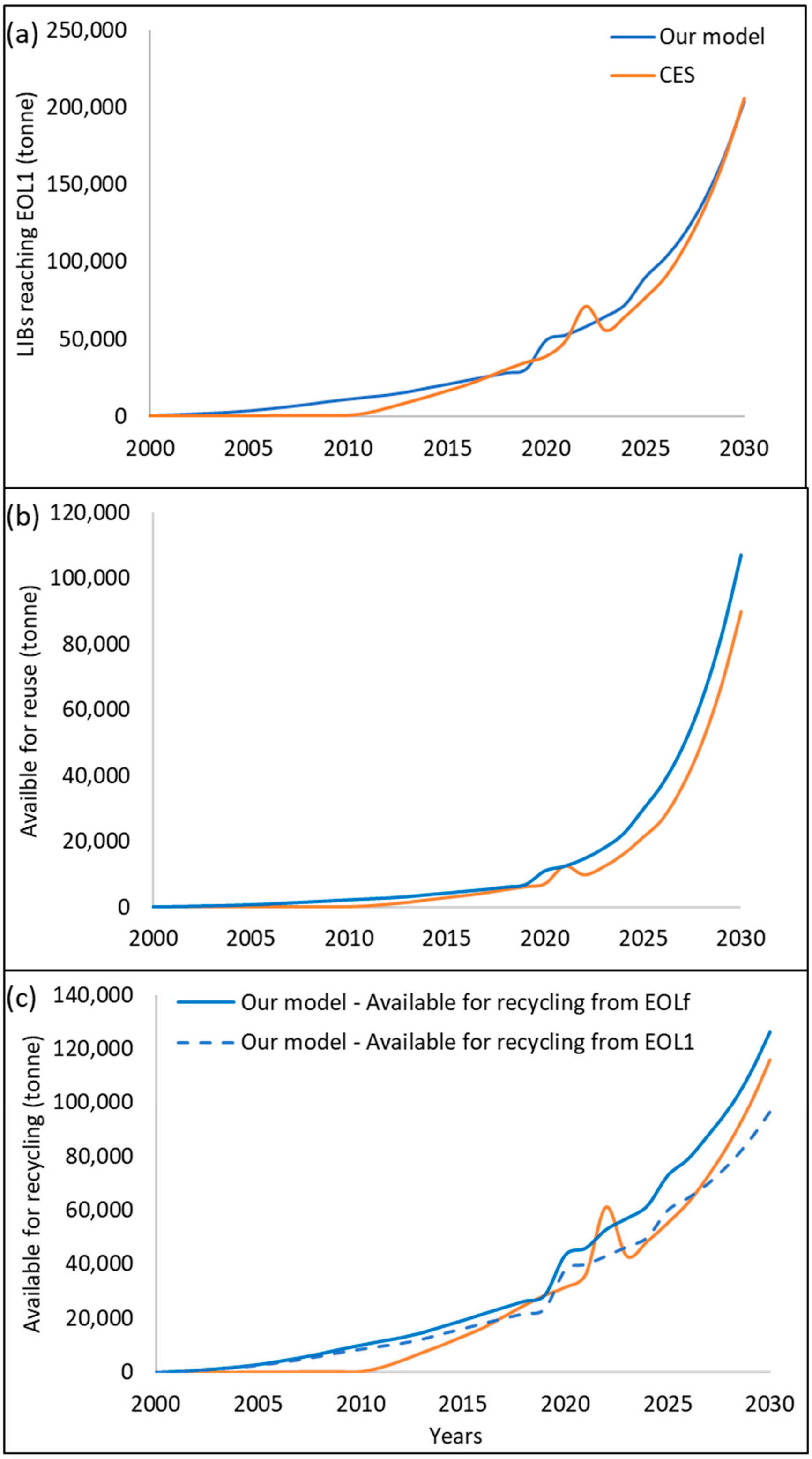


Figure S13. Comparison between our model and CES's model

8. Result comparison with literature

Several studies have focused on the recovery of materials or elements from EV recycling, and we have compiled a summary of these relevant studies in Table S16. It's important to note that our study specifically focuses on U.S. LIBs and as a result, we compare our findings with studies also consider U.S. EV LIB recycling. The results comparison can be found in Figure S14. From the comparison, the % of Li contained in POM that can be satisfied by recycling from our study is less than the two other studies which concentrate in the U.S. The primary factor contributing to the disparity is the EOL probability distribution. Our study relies on empirical data for the EOL probability distribution, while other studies utilize mathematical probability distributions. However, there is consensus that there won't be major contribution from recycling until after 2030.

Table S16. A summary of material flow analysis studies pertaining to EV recycling

	Region	Years	Data	Baseline scenario	Main findings
Xu et al. [38]	Global	2020-2050	EV fleet development scenario of the IEA till 2030 and a logistic model to extrapolate the EV fleet penetration until 2050	The stated policies (STEP) scenario and the sustainable development (SD) scenario	The findings indicate that battery recycling has the potential to reduce cumulative material demand for Li by 20-23%, for Co by 26-44%, an d22-38% for Ni from 2020-2050.
Dunn et al. [6]	Global and regional (US, EU, China, and rest of world)	2020-2040	(1) future EV sales; (2) the capacity of batteries in sold vehicles; (3) the cathode material composition.	Diffusion model with policy-based target and market forecast based on an estimate by BM.	Under the idealized conditions, where there is no export, 100% collection, and only a 5% loss during recycling, the material obtained from retired batteries in 2040 has the potential to fulfill 58% of material demand in China, 60% of demand in the US, and 48% of pack material demand in Europe. - 2030 lithium data
Shafique et al. [4]	US and China	2020-2030	Previous sales and future promotion policies on adopting BEVs in China and U.S.; specific energy and battery size; Weibull distribution for lifespan	Three different scenarios by varying lifetime, recycling efficiency, and battery second use percentage	The demand for materials used in LIB batteries, such as Li, is projected to rise significantly from 3 kT in 2020 to 33 kT in 2030. The research findings indicate that by 2030, there will be approximately 2.5–3.8 kT of Li stock available for recycling (depending on the recycling scenario) in the USA alone. Similarly, the future demand for Co is expected to increase from 4 kT in 2020 to 43 kT by 2030. Furthermore, the results demonstrate that the amount of Co reaching its end-of-life (EOL) is set to increase from 0.2 kT to around 3–5 kT by 2030 in the USA. In 2030, it is estimated that only 0.82 kT of Li and 0.86 kT of Co will be available from EOL and R2R

Neidhardt et al. [2]	Global	2020-2035	Sales number based on different projections, regional share split, average battery capacity, and lifetime.		This article is trying to find the break-even points for each critical materials: when secondary critical element can be sufficient to satisfy the demand. Secondary Co supply will be sufficient to start satisfying the demand between 2029 to 2035. The gap between secondary material availability and material demand is increasing for Li and Ni for all scenarios.
Abdelbaky et al. [3]	EU	2010-2040	Life time distribution, vehicle sales forecast, and projected yearly energy capacities	The baseline scenario builds on the commercialization dates of future technologies and the 2030 technology mix of the new policies scenario from the IEA outlook study (IEA, 2018).	Baseline: in 2030, waste stream contains 1.3 kT of lithium, which is equivalent to 5% of Europe's demand for lithium for passenger electric vehicles in the same year. In 2040, waste stream contains 15 kT of lithium, which is equivalent to 19% of the projected demand in 2040.
Richa et al. [5]	US	2015-2040	Projected EV sales, battery, and vehicle lifespans		In the baseline scenario, the total mass of EV battery waste stream is projected as follows: 3 kT in 2020, 25 kt in 2025, 56 kT in 2030, 97 kT in 2035, and 143 kT in 2040. Within the baseline scenario, the waste stream composition consists of approximately 1.38% lithium, 3.97% cobalt, and 2.44% nickel.

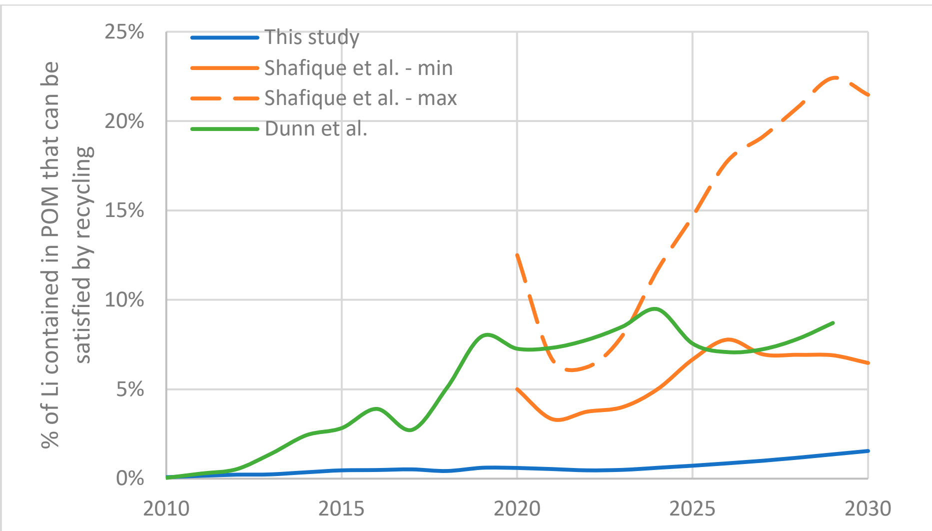


Figure S14. Comparison of % of Li contained in POM that can be satisfied by recycling (for comparison purposes, the scenario compared from Dunn's paper is S3 (IEA MoMo model) + C2 (chemistry composition prediction from Benchmark Mineral))

9. Upper and lower bounds of the model

Tables S17 and S18 show a summary of average values, lower bounds, and upper bounds used for different input parameters. The new factory construction and factory expansion rate is also a changing input parameter, and for simplification purposes, the lower and upper bounds have been discussed in Section 3.2 separately. As shown in Figure S15, it is clear that even if all material available for recycling can be recovered with 100% efficiency, there is still a need for raw material extraction, imports, or recovery of competing materials.

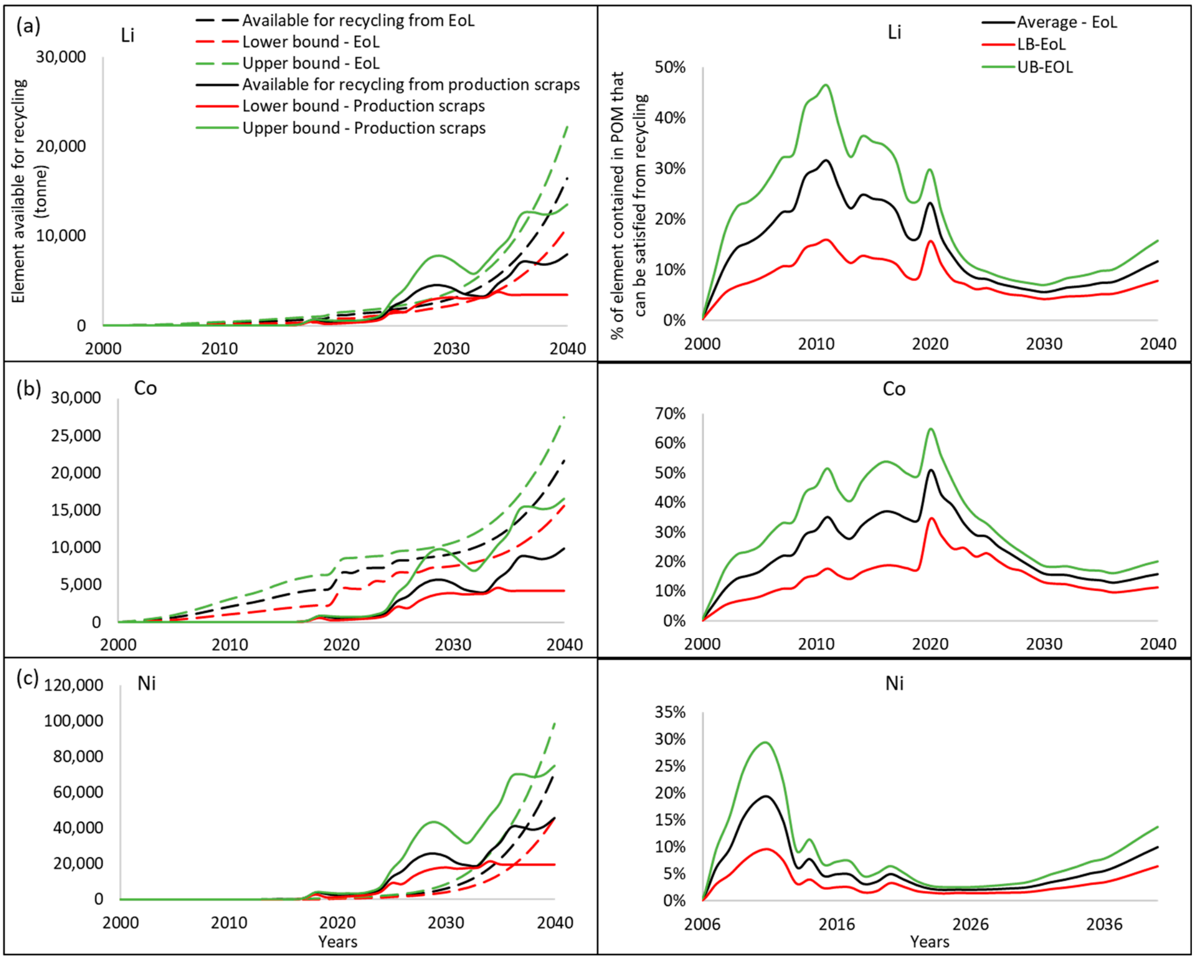
Table S17. Summary of average value, lower bound, and upper bound used for different input parameters

Average, lower bound, and upper bound	Notes
Stored %	5% (average); 1% (lower bound); 10% (upper bound)
Lost %	Table S18
Exported %	Table S3
Reuse %	Table S5
Reuse time	Table S5
Production maturity time	4 years (average); 2 years (lower bound); 4 years (upper bound)

Table S18. Assumed lost rate for LIBs contained in portable devices

Lifespan (years)	1	2	3	4	5	6	7	8	9	10	11	12
Average lost rate (%)	0.0	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Lower bound for lost rate (%)	0.0	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Upper bound for lost rate (%)	0.0	1.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0

Figure S15. (a), (b), and (c) Average, lower bound, and upper bound of elements that can be recovered from LIBs available for recy



cling from EOL$_f$ and from production scrap (100% recovery efficiency); (d), (e), and (f) average, lower bound, and upper bound of percentage of elements contained in POM that can be satisfied from recycling