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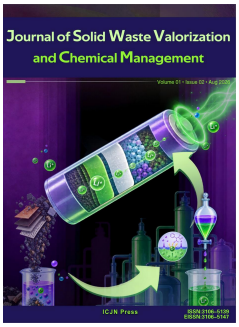

Supplementary Information

Synergistic Pathways for Pollution and Carbon Reduction in End-of-Life Nickel Cobalt Manganese Oxide Battery Recycling Processes

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Table S1. Life cycle inventory of pyrometallurgy for EOL NCM batteries

Type		Parameter	Amount	Unit
Input	Material	EOL NCM battery	1.00×10^{0}	kg
		Limestone	1.36×10^{0}	kg
		Sulfuric acid	3.88×10^{0}	kg
		Sodium hydroxide	2.88×10^{0}	kg
		Hydrogen peroxide	8.50×10^{-2}	kg
		Lithium carbonate	1.90×10^{-1}	kg
	Energy	Electricity	5.40×10^{-2}	MJ
		Natural gas	7.40×10^{0}	MJ
Output	Products	Aluminium	1.40×10^{-1}	kg
		Copper	9.80×10^{-1}	kg
		Nickel	9.60×10^{-1}	kg
		Cobalt	3.20×10^{-1}	kg
	Atmospheric pollutants	Carbon dioxide	1.03×10^{1}	kg

NOTE: EOL: end-of-life; NCM: nickel cobalt manganese oxide.

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Table S2. Life cycle inventory of hydrometallurgy for EOL NCM batteries

Type		Parameter	Amount	Unit
Input	Material	EOL NCM battery	1.00×10^{0}	kg
		N-Methyl-2-pyrrolidone	6.38×10^{-1}	kg
		Decarbonised water	5.14×10^{1}	kg
		Nitrogen	1.08×10^{-2}	kg
		Sulfuric acid	9.32×10^{-1}	kg
		Hydrochloric acid	1.52×10^{-2}	kg
		Hydrogen peroxide	1.41×10^{-1}	kg
		Ammonia	1.93×10^{-2}	kg
		Sodium hydroxide	7.11×10^{-1}	kg
		Sodium carbonate	2.09×10^{-1}	kg
		Lithium carbonate	8.10×10^{-3}	kg
		Deionised water	5.37×10^{0}	kg
	Energy	Electricity	2.71×10^{0}	kWh
		Steam	9.49×10^{-1}	kg
		Heat	7.77×10^{0}	MJ
Output	Products	Chromium steel 18/8	1.10×10^{-2}	kg
		Aluminium	7.54×10^{-2}	kg
		Copper	7.90×10^{-2}	kg
		Cathode active material	3.80×10^{-1}	kg
	Atmospheric pollutants	Carbon dioxide	9.70×10^{-1}	kg
	Waste	Waste copper	6.99×10^{-4}	kg
		Waste aluminium	3.97×10^{-3}	kg
		Waste printed wiring board	2.99×10^{-3}	kg
		Waste chromium steel 18/8	9.59×10^{-4}	kg
		Waste coolant	2.63×10^{-2}	kg
		Waste fiberglass	5.59×10^{-2}	kg
		Waste steel	3.39×10^{-3}	kg
		Waste PP	4.38×10^{-3}	kg
		Waste PE	9.67×10^{-4}	kg
		Waste PET	1.16×10^{-3}	kg
		Waste sludge	7.49×10^{0}	kg
		Waste PVDF	1.28×10^{-2}	kg

NOTE: PP: polypropylene; PE: polyethylene; PET: polyethylene terephthalate; PVDF: polyvinylidene fluoride.

Table S3. Life cycle inventory of pyro-hydrometallurgy for EOL NCM batteries

Type		Parameter	Amount	Unit
Input	Material	EOL NCM battery	1.00×10^{0}	kg
		Hydrochloric acid	2.33×10^{2}	kg
		Hydrogen peroxide	3.28×10^{1}	kg
		Laterite, mineral	1.70×10^{2}	kg
		Lime	4.90×10^{1}	kg
		Limestone	1.70×10^{2}	kg
		Petroleum coke	1.87×10^{2}	kg
		Tap water	1.40×10^{1}	kg
	Energy	Electricity	1.36×10^{3}	kWh
Output	Products	Ternary precursor	3.13×10^{2}	kg
		Lithium carbonate	1.18×10^{2}	kg
	Atmospheric pollutants	Carbon dioxide	4.17×10^{2}	kg

Table S4. Life cycle inventory of direct recycling for EOL NCM batteries

Type		Parameter	Amount	Unit
Input	Material	EOL NCM battery	1.00×10^{0}	kg
		Lithium hydroxide	4.00×10^{-2}	kg
		Lithium carbonate	3.75×10^{-3}	kg
		Sodium chloride	7.35×10^{-3}	kg
	Energy	Electricity	4.00×10^{-1}	kWh
		Steam	7.20×10^{-1}	kg
Output	Products	Ternary cathode materials	1.70×10^{-1}	kg
		Copper	1.10×10^{-1}	kg
		Aluminium	8.00×10^{-2}	kg
	Atmospheric pollutants	Dust	8.70×10^{-4}	kg
		Total non-methane hydrocarbons	1.34×10^{-4}	kg
	Waste	Solid waste	3.00×10^{-2}	kg

Text S1. Substitution-ratio sensitivity analysis.

The environmental benefits attributed to recycled materials depend not only on the environmental burdens of the recycling processes themselves, but also on the extent to which recovered products can displace functionally equivalent virgin products. In recycling-oriented life cycle assessment (LCA), avoided virgin-material production is commonly used to account for the environmental benefits associated with secondary-material recovery, whereas the magnitude of this credit depends on the substitutability between recycled and virgin products[3-4]. Previous studies have emphasized that assuming a one-to-one substitution ratio may not adequately capture differences in technical functionality, material quality, product purity, and downstream application requirements[5]. Therefore, a substitution-ratio sensitivity analysis is conducted to examine whether the comparative environmental performance of the four recycling routes is sensitive to different assumptions regarding recycled-material substitution.

The original results were first used as the reference, in which recovered products were treated as outputs of the recycling processes without assigning avoided-production credits for the displacement of virgin products. To determine the environmental adjustment associated with full substitution, additional product-system models were constructed in openLCA for the four recycling routes. The functional unit, foreground material and energy inputs, direct emissions, background database, and life cycle impact assessment (LCIA) method were kept unchanged from the corresponding baseline scenario (BAU) models. The principal recovered products were linked to their functionally corresponding virgin products and treated as avoided products. Under the 100% substitution ratio (SR100) assumption, the credited amount of each recovered product is equal to its modeled output amount, corresponding to a 1:1 displacement of the functionally equivalent virgin

product. The environmental impact associated with full substitution is calculated directly using openLCA. The difference between the original BAU result and the SR100 result is then defined as the environmental adjustment associated with 100% substitution:

$$\Delta EI_{j,k}^{100}=EI_{j,k}^{BAU}-EI_{j,k}^{SR100} \quad (S1)$$

where $\Delta EI_{j,k}^{100}$ represents the environmental impact of recycling route j for impact category k without avoided virgin-production credits; $EI_{j,k}^{BAU}$ represents the corresponding net environmental impact under the full-substitution assumption; and $EI_{j,k}^{SR100}$ represents the environmental adjustment resulting from the complete displacement of the corresponding virgin products. Based on this full-substitution adjustment, the environmental impacts under different substitution ratios were calculated as:

$$EI_{j,k}^{SR}=EI_{j,k}^{BAU}-SR\times\Delta EI_{j,k}^{SR100} \quad (S2)$$

where SR is the assumed substitution ratio, values of 0.50, 0.80, and 1.00 were examined to represent different degrees of functional displacement of virgin products. For example, SR50 assigns 50% of the avoided-production adjustment obtained under full substitution, whereas SR100 assigns the complete avoided-production adjustment. These substitution ratios were used as sensitivity parameters to assess the dependence of the comparative LCA results on recycled-material substitution assumptions.

Table S5. Environmental impacts of the four EOL NCM battery recycling routes under different recycled-material substitution ratios

Recycling Process	Impact Category	Unit	SR50	SR80	SR100
Pyrometallurgical recycling	GWP	kg CO_2-eq	4.8104×10^{0}	3.3118×10^{0}	2.3128×10^{0}
	TA	kg SO_2-eq	5.6147×10^{-2}	4.8461×10^{-2}	4.3338×10^{-2}
	FEC	kg 1,4-DCB-eq	3.4344×10^{-1}	2.2779×10^{-1}	1.5069×10^{-1}
	MEC	kg 1,4-DCB-eq	4.3538×10^{-1}	2.7769×10^{-1}	1.7256×10^{-1}
	TEC	kg 1,4-DCB-eq	2.0306×10^{1}	1.8491×10^{1}	1.7281×10^{1}
	FRD	kg oil-eq	1.4135×10^{0}	1.0897×10^{0}	8.7387×10^{-1}
	FEU	kg P-eq	2.0159×10^{-3}	1.3173×10^{-3}	8.5156×10^{-4}
	MEU	kg N-eq	1.8342×10^{-3}	1.7869×10^{-3}	1.7554×10^{-3}
	HCT	kg 1,4-DCB-eq	-6.5335×10^{-1}	-1.9790×10^{0}	-2.8627×10^{0}
	HNT	kg 1,4-DCB-eq	-1.9001×10^{1}	-3.7927×10^{1}	-5.0545×10^{1}
	IR	kBq Co-60-eq	4.0908×10^{-1}	3.8819×10^{-1}	3.7427×10^{-1}
	LU	m^2a crop-eq	1.2369×10^{-1}	1.0845×10^{-1}	9.8293×10^{-2}
	MRD	kg Cu-eq	9.2146×10^{0}	9.8627×10^{0}	1.0295×10^{1}
	ODP	kg CFC-11-eq	2.1860×10^{-6}	1.9131×10^{-6}	1.7312×10^{-6}
	PMF	kg $PM_{2.5}$-eq	1.6042×10^{-2}	1.0219×10^{-2}	6.3366×10^{-3}
	POF-HH	kg NO_x-eq	1.5580×10^{-2}	1.2268×10^{-2}	1.0059×10^{-2}
	POF-TE	kg NO_x-eq	1.6119×10^{-2}	1.2752×10^{-2}	1.0507×10^{-2}
	WD	m^3	1.5044×10^{-1}	1.4570×10^{-1}	1.4254×10^{-1}
Hydrometallurgical recycling	GWP	kg CO_2-eq	8.5367×10^{0}	7.8531×10^{0}	7.3973×10^{0}
	TA	kg SO_2-eq	4.8579×10^{-2}	4.5668×10^{-2}	4.3727×10^{-2}
	FEC	kg 1,4-DCB-eq	3.9268×10^{-1}	3.5850×10^{-1}	3.3571×10^{-1}
	MEC	kg 1,4-DCB-eq	5.0557×10^{-1}	4.5866×10^{-1}	4.2739×10^{-1}
	TEC	kg 1,4-DCB-eq	1.4252×10^{1}	1.3259×10^{1}	1.2596×10^{1}
	FRD	kg oil-eq	2.5969×10^{0}	2.4363×10^{0}	2.3293×10^{0}
	FEU	kg P-eq	2.0228×10^{-3}	1.6348×10^{-3}	1.3762×10^{-3}
	MEU	kg N-eq	3.2042×10^{-4}	2.9514×10^{-4}	2.7828×10^{-4}
	HCT	kg 1,4-DCB-eq	7.9098×10^{-1}	3.5525×10^{-1}	6.4759×10^{-2}
	HNT	kg 1,4-DCB-eq	8.5661×10^{0}	7.3440×10^{0}	6.5292×10^{0}
	IR	kBq Co-60-eq	4.8434×10^{-1}	4.8095×10^{-1}	4.7868×10^{-1}
	LU	m^2a crop-eq	1.5162×10^{-1}	1.4479×10^{-1}	1.4024×10^{-1}
	MRD	kg Cu-eq	5.2524×10^{-1}	5.1539×10^{-1}	5.0882×10^{-1}
	ODP	kg CFC-11-eq	1.7252×10^{-6}	1.5889×10^{-6}	1.4981×10^{-6}
	PMF	kg $PM_{2.5}$-eq	1.4120×10^{-2}	1.1240×10^{-2}	9.3203×10^{-3}
	POF-HH	kg NO_x-eq	1.8685×10^{-2}	1.7036×10^{-2}	1.5937×10^{-2}

Table S5. Environmental impacts of the four EOL NCM battery recycling routes under different recycled-material substitution ratios (continued)

Recycling process	Impact category	Unit	SR50	SR80	SR100
Hydrometallurgical recycling	POF-TE	kg NO_x-eq	1.9665×10^{-2}	1.7995×10^{-2}	1.6882×10^{-2}
	WD	m^3	2.0978×10^{-1}	2.0740×10^{-1}	2.0582×10^{-1}
Pyro-hydrometallurgical recycling	GWP	kg CO_2-eq	1.7997×10^{0}	1.7310×10^{0}	1.6852×10^{0}
	TA	kg SO_2-eq	5.9019×10^{-3}	5.6230×10^{-3}	5.4371×10^{-3}
	FEC	kg 1,4-DCB-eq	4.9818×10^{-2}	4.6786×10^{-2}	4.4764×10^{-2}
	MEC	kg 1,4-DCB-eq	6.6756×10^{-2}	6.2617×10^{-2}	5.9858×10^{-2}
	TEC	kg 1,4-DCB-eq	1.3650×10^{0}	1.0524×10^{0}	8.4395×10^{-1}
	FRD	kg oil-eq	4.8711×10^{-1}	4.2930×10^{-1}	3.9077×10^{-1}
	FEU	kg P-eq	4.1561×10^{-4}	4.0785×10^{-4}	4.0268×10^{-4}
	MEU	kg N-eq	3.7600×10^{-5}	3.4456×10^{-5}	3.2360×10^{-5}
	HCT	kg 1,4-DCB-eq	2.9067×10^{-1}	2.7597×10^{-1}	2.6617×10^{-1}
	HNT	kg 1,4-DCB-eq	1.9059×10^{0}	1.8214×10^{0}	1.7651×10^{0}
	IR	kBq Co-60-eq	3.3752×10^{-2}	3.1725×10^{-2}	3.0374×10^{-2}
	LU	m^2a crop-eq	-6.2692×10^{-2}	-1.2606×10^{-1}	-1.6831×10^{-1}
	MRD	kg Cu-eq	3.6669×10^{-2}	3.4994×10^{-2}	3.3877×10^{-2}
	ODP	kg CFC-11-eq	2.9765×10^{-7}	2.3416×10^{-7}	1.9183×10^{-7}
	PMF	kg $PM_{2.5}$-eq	2.8204×10^{-3}	2.6768×10^{-3}	2.5810×10^{-3}
	POF-HH	kg NO_x-eq	4.7307×10^{-3}	4.2799×10^{-3}	3.9793×10^{-3}
	POF-TE	kg NO_x-eq	4.8057×10^{-3}	4.3215×10^{-3}	3.9986×10^{-3}
	WD	m^3	8.7356×10^{-3}	7.7873×10^{-3}	7.1551×10^{-3}
Direct recycling	GWP	kg CO_2-eq	1.2153×10^{-1}	-6.1327×10^{-1}	-1.1031×10^{0}
	TA	kg SO_2-eq	6.4705×10^{-4}	-2.4898×10^{-3}	-4.5810×10^{-3}
	FEC	kg 1,4-DCB-eq	2.1968×10^{-2}	-3.8564×10^{-3}	-2.1072×10^{-2}
	MEC	kg 1,4-DCB-eq	2.5655×10^{-2}	-1.0547×10^{-2}	-3.4681×10^{-2}
	TEC	kg 1,4-DCB-eq	3.1528×10^{0}	2.6331×10^{0}	2.2867×10^{0}
	FRD	kg oil-eq	4.4547×10^{-2}	-1.2795×10^{-1}	-2.4296×10^{-1}
	FEU	kg P-eq	-2.1259×10^{-4}	-6.2170×10^{-4}	-8.9444×10^{-4}
	MEU	kg N-eq	4.3942×10^{-4}	4.1233×10^{-4}	3.9426×10^{-4}
	HCT	kg 1,4-DCB-eq	-3.9871×10^{-1}	-7.6655×10^{-1}	-1.0118×10^{0}
	HNT	kg 1,4-DCB-eq	2.6966×10^{-1}	-6.7207×10^{-1}	-1.2999×10^{0}
	IR	kBq Co-60-eq	2.1722×10^{-2}	1.8961×10^{-2}	1.7119×10^{-2}
	LU	m^2a crop-eq	1.3500×10^{-2}	6.6198×10^{-3}	2.0329×10^{-3}
	MRD	kg Cu-eq	2.0599×10^{0}	2.0511×10^{0}	2.0451×10^{0}
	ODP	kg CFC-11-eq	4.5985×10^{-8}	-9.9379×10^{-8}	-1.9629×10^{-8}
	PMF	kg $PM_{2.5}$-eq	-2.7802×10^{-3}	-5.8868×10^{-3}	-7.9579×10^{-3}
	POF-HH	kg NO_x-eq	9.3674×10^{-4}	-8.3306×10^{-4}	-2.0129×10^{-3}
	POF-TE	kg NO_x-eq	1.0008×10^{-3}	-7.9001×10^{-4}	-1.9839×10^{-3}
	WD	m^3	4.4398×10^{-3}	1.9853×10^{-3}	3.4899×10^{-4}

Note: GWP: global warming potential; TA: terrestrial acidification; FEC: freshwater ecotoxicity; MEC: marine ecotoxicity; TEC: terrestrial ecotoxicity; FRD: fossil resource depletion; FEU: freshwater eutrophication; MEU: marine eutrophication; HCT: human carcinogenic toxicity; HNT: human noncarcinogenic toxicity; IR: ionizing radiation; LU: land use; MRD: mineral resource depletion; ODP: ozone depletion; PMF: particulate matter formation; POF-HH: photochemical oxidant formation (human health); POF-TE: photochemical oxidant formation (terrestrial ecosystems); WD: water depletion; SR: substitution ratio. SR50, SR80, and SR100 represent substitution-adjusted net environmental impacts at substitution ratios of 50%, 80%, and 100%, respectively. Negative values indicate that avoided virgin-production burdens exceed gross recycling-process burdens for the corresponding impact category.

The substitution-ratio sensitivity analysis indicates that the principal global warming potential (GWP) comparison is robust. The GWP ranking remains Direct recycling < Pyro-hydrometallurgical recycling < Pyrometallurgical recycling < Hydrometallurgical recycling under SR50, SR80, and SR100. For direct recycling, GWP changes from 1.3462 kg under BAU to 0.1215, -0.6133, and -1.1031 under SR50, SR80, and SR100, respectively. Across the 18 midpoint impact categories, the best-performing route remains unchanged in 12 (66.7%). Ranking changes occur for FEC, MEC, FEU, HCT, HNT, and LU. FEC, MEC, and FEU shift from pyro-hydrometallurgical recycling under BAU to

direct recycling after substitution credits are introduced; HCT and HNT shift from direct recycling to pyrometallurgical recycling; and LU shifts from direct recycling to pyro-hydrometallurgical recycling. The best-performing route is identical across SR50, SR80, and SR100 for all 18 categories, indicating that within the tested substitution range, increasing the substitution ratio primarily changes the magnitude of the net environmental results rather than the preferred route.

Figure. S1 summarizes the distribution of GWP results across the investigated recycled-material substitution ratios. The four recycling routes show different degrees of change in GWP as the substitution ratio changes, indicating that the magnitude of net climate benefits is sensitive to the assumed displacement of virgin materials. Nevertheless, the relative GWP ranking of the four routes remains unchanged across the investigated substitution conditions, supporting the robustness of the GWP-based comparison.

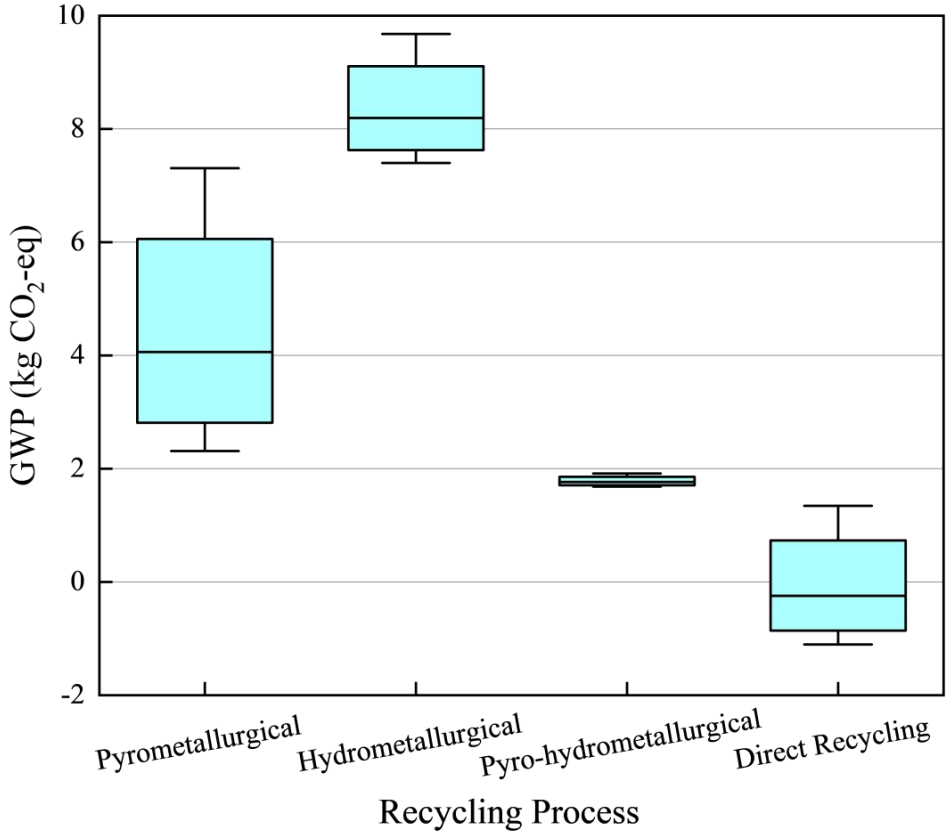

Figure S1. Sensitivity analysis of global warming potential (GWP) to the recycled-material substitution ratios for the four end-of-life (EOL) nickel cobalt manganese oxide (NCM) battery recycling processes.

Table S6. Parameter adjustments for the four EOL NCM battery recycling processes under different scenarios

Scenario	Recycling Process	Adjusted Parameter(s)	Adjustment Method	LCA Model Implementation
Baseline Scenario (BAU)	Pyrometallurgy	/	/	Use the baseline life-cycle inventory and baseline electricity structure
	Hydrometallurgy			
	Pyro-hydrometallurgy			
	Direct recycling			
Technology Progress Scenario (TPS)	Pyrometallurgy	NaOH and H_2SO_4	Each reduced by 10% relative to BAU.	Adjust the corresponding material inputs in the foreground inventory; keep all other parameters unchanged
	Hydrometallurgy	NMP and NaOH		
	Pyro-hydrometallurgy	HCl and H_2O_2		
	Direct recycling	LiOH and steam		
Energy Structure Transition Scenario (ETS)	Pyrometallurgy	Electricity structure	Replace the baseline electricity mix with a low-carbon electricity structure consistent with the 1.5 °C target; keep electricity consumption unchanged	Replace only the background electricity process; do not change material or energy input amounts in the foreground inventory
	Hydrometallurgy			
	Pyro-hydrometallurgy			
	Direct recycling			

Table S6. Parameter adjustments for the four EOL NCM battery recycling processes under different scenarios (continued)

Scenario	Recycling Process	Adjusted Parameter(s)	Adjustment Method	LCA Model Implementation
Combined Scenario (CS)	Pyrometallurgy	NaOH, H_2SO_4, and electricity structure	NaOH and H_2SO_4 are each reduced by 10%; simultaneously apply the low-carbon electricity structure consistent with the 1.5 °C target	Adjust foreground material inputs and replace the background electricity process simultaneously
	Hydrometallurgy	NMP, NaOH, and electricity structure	NMP and NaOH are each reduced by 10%; simultaneously apply the low-carbon electricity structure consistent with the 1.5 °C target	
	Pyro-hydrometallurgy	HCl, H_2O_2, and electricity structure	HCl and H_2O_2 are each reduced by 10%; simultaneously, apply the low-carbon electricity structure consistent with the 1.5 °C target	
	Direct recycling	LiOH, steam, and electricity structure	LiOH and steam are each reduced by 10%; simultaneously, apply the low-carbon electricity structure consistent with the 1.5 °C target	

Note: BAU: the baseline scenario; TPS: technology progress scenario; ETS: energy structure transition scenario; CS: combined scenario; NMP: N-methyl-2-pyrrolidone; NaOH: sodium hydroxide; H_2SO_4: sulfuric acid; HCl: hydrochloric acid; H_2O_2: hydrogen peroxide; LiOH: lithium hydroxide. The key parameters in the TPS scenario were determined through contribution hotspot and sensitivity analyses, and their values were set to decrease by 10% relative to the baseline scenario. The ETS scenario adopts a low-carbon electricity structure consistent with the 1.5 °C climate target. It changes only the background electricity structure and keeps electricity consumption unchanged, thereby distinguishing the effect of energy structure optimization from that of process energy-efficiency improvement.

Table S7. Synergy indices between GWP reduction and environmental impact categories for four EOL NCM battery recycling processes under three optimization scenarios

Recycling Process	Impact Category	Original Unit	TPS	ETS	CS
Pyrometallurgical Recycling	TA	kg SO_2-eq	1.30	0.27	1.27
	FEC	kg 1,4-DCB-eq	1.03	0.16	1.01
	MEC	kg 1,4-DCB-eq	1.03	0.17	1.01
	TEC	kg 1,4-DCB-eq	0.99	-0.35	0.95
	FRD	kg oil-eq	0.97	0.82	0.96
	FEU	kg P-eq	1.03	0.43	1.02
	MEU	kg N-eq	0.22	0.04	0.22
	HCT	kg 1,4-DCB-eq	1.14	0.59	1.13
	HNT	kg 1,4-DCB-eq	1.06	0.35	1.04
	IR	kBq Co-60-eq	1.36	0.02	1.32
	LU	m^2a crop-eq	1.06	-28.62	0.27
	MRD	kg Cu-eq	0.10	0.00	0.10
	ODP	kg CFC-11-eq	1.16	-0.81	1.11
	PMF	kg $PM_{2.5}$-eq	1.29	0.26	1.26
	POF-HH	kg NO_x-eq	0.92	0.17	0.90
	POF-TE	kg NO_x-eq	0.92	0.16	0.90
	WD	m^3	1.34	0.08	1.30
Hydrometallurgical Recycling	TA	kg SO_2-eq	0.57	0.47	0.50
	FEC	kg 1,4-DCB-eq	0.78	0.26	0.40
	MEC	kg 1,4-DCB-eq	0.79	0.27	0.41
	TEC	kg 1,4-DCB-eq	1.03	-0.68	-0.21
	FRD	kg oil-eq	0.99	0.74	0.81
	FEU	kg P-eq	1.06	0.68	0.78
	MEU	kg N-eq	0.72	0.29	0.41
	HCT	kg 1,4-DCB-eq	0.99	0.80	0.85
	HNT	kg 1,4-DCB-eq	1.00	0.55	0.68
	IR	kBq Co-60-eq	1.04	0.03	0.31
	LU	m^2a crop-eq	1.07	-34.65	-24.76
	MRD	kg Cu-eq	0.43	0.01	0.12
	ODP	kg CFC-11-eq	1.04	-1.44	-0.75
	PMF	kg $PM_{2.5}$-eq	0.73	0.48	0.55
	POF-HH	kg NO_x-eq	1.06	0.23	0.46
	POF-TE	kg NO_x-eq	1.05	0.21	0.44
	WD	m^3	0.97	0.08	0.32
Pyro-Hydrometallurgical Recycling	TA	kg SO_2-eq	1.01	0.77	0.81
	FEC	kg 1,4-DCB-eq	1.05	0.42	0.50

Table S7. Synergy indices between GWP reduction and environmental impact categories for four EOL NCM battery recycling processes under three optimization scenarios (continued)

Recycling Process	Impact Category	Original Unit	TPS	ETS	CS
Pyro-Hydrometallurgical Recycling	MEC	kg 1,4-DCB-eq	1.05	0.42	0.50
	TEC	kg 1,4-DCB-eq	0.99	-1.13	-0.84
	FRD	kg oil-eq	0.77	0.72	0.72
	FEU	kg P-eq	1.06	0.83	0.86
	MEU	kg N-eq	0.96	0.49	0.56
	HCT	kg 1,4-DCB-eq	1.02	0.76	0.80
	HNT	kg 1,4-DCB-eq	1.06	0.57	0.63
	IR	kBq Co-60-eq	0.99	0.06	0.19
	LU	m^2a crop-eq	0.63	-26.03	-22.34
	MRD	kg Cu-eq	0.95	0.02	0.15
	ODP	kg CFC-11-eq	0.97	-1.38	-1.06
	PMF	kg $PM_{2.5}$-eq	1.02	0.58	0.64
	POF-HH	kg NO_x-eq	1.01	0.18	0.29
	POF-TE	kg NO_x-eq	0.99	0.16	0.28
	WD	m^3	1.03	0.32	0.42
Direct Recycling	TA	kg SO_2-eq	0.99	0.59	0.70
	FEC	kg 1,4-DCB-eq	0.97	0.25	0.45
	MEC	kg 1,4-DCB-eq	0.97	0.25	0.46
	TEC	kg 1,4-DCB-eq	0.99	-0.37	0.02
	FRD	kg oil-eq	1.00	0.88	0.92
	FEU	kg P-eq	0.98	0.54	0.66
	MEU	kg N-eq	0.96	0.03	0.30
	HCT	kg 1,4-DCB-eq	0.99	0.79	0.85
	HNT	kg 1,4-DCB-eq	0.98	0.44	0.60
	IR	kBq Co-60-eq	0.98	0.06	0.33
	LU	m^2a crop-eq	0.99	-31.48	-22.20
	MRD	kg Cu-eq	0.96	0.00	0.27
	ODP	kg CFC-11-eq	0.99	-1.36	-0.69
	PMF	kg $PM_{2.5}$-eq	0.99	0.52	0.66
	POF-HH	kg NO_x-eq	0.99	0.17	0.41
	POF-TE	kg NO_x-eq	0.99	0.16	0.40
	WD	m^3	0.98	0.27	0.47

Note: SI: synergy index. SI is calculated as the ratio of the reduction rate of each non-GWP impact category to the GWP reduction rate under the same process and scenario. SI > 1 indicates that the reduction in the corresponding impact category is greater than the GWP reduction; 0 < SI < 1 indicates that GWP reduction is more pronounced; SI < 0 indicates potential environmental burden shifting. Pollution-related categories include TA, FEC, MEC, TEC, FEU, MEU, HCT, HNT, ODP, PMF, POF-HH, and POF-TE.

Text S2. Entropy-weighted calculation of the average pollution-related reduction rate

The entropy weight method (EWM) is an objective weighting approach that assigns indicator weights based on the amount of information captured by changes in observed data. To avoid assigning equal importance to pollution-related environmental impact categories, EWM is employed to determine objective weights for the 12 pollution-related impact categories[1-2], including TA, FEC, MEC, TEC, FEU, MEU, HCT, HNT, ODP, PMF, POF-HH, and POF-TE.

The entropy weights were derived from the environmental impact results of the four recycling routes under the BAU. Using BAU data to determine weights provides a common basis for all optimization scenarios and avoids scenario-specific changes in indicator weights driven by environmental performance. The resulting weights were therefore held constant when calculating the entropy-weighted average pollution-related reduction rate (AER) under the TPS, ETS, and CS scenarios.

Let x_{ik} denote the BAU environmental impact value of recycling route i for pollution-related impact category k, where i=1,…,n, n=4, and k=1,…,m, m=12. Since all environmental impact categories are burden-type indicators, for which a lower value represents better environmental performance, the original data were normalized as:

$$z_{ik}=\frac{x_k^{max}-x_{ik}}{x_k^{max}-x_k^{min}} \tag{S3}$$

where x_k^{max} and x_k^{min} are the maximum and minimum BAU impact values of category k among the four recycling routes. The proportion of recycling route i for impact category k is then calculated as:

$$p_{ik}=\frac{z_{ik}}{\sum_{i=1}^{n} z_{ik}} \tag{S4}$$

The information entropy of impact category k is calculated as:

$$e_k=-\frac{1}{\ln n}\sum_{i=1}^{n} p_{ik}\ln p_{ik} \tag{S5}$$

where 0ln0 is defined as 0. The corresponding information utility, or divergence coefficient, is determined as:

$$d_k=1-e_k \tag{S6}$$

Finally, the entropy weight of impact category k is calculated as:

$$w_k=\frac{d_k}{\sum_{k=1}^{m} d_k} \tag{S7}$$

where $\sum_{k=1}^{m} w_k=1$. A larger weight indicates that the corresponding environmental impact category provides greater discriminatory information across the four recycling routes under the BAU scenario.

For recycling route j under optimization scenario s, the reduction rate of pollution-related impact category k relative to BAU is calculated as:

$$ER_{j,k,s}=\frac{EI_{j,k,0}-EI_{j,k,s}}{EI_{j,k,0}} \tag{S8}$$

The entropy-weighted average pollution-related reduction rate is subsequently calculated as:

$$AER_{j,s}=\sum_{k=1}^{12} w_k ER_{j,k,s} \tag{S9}$$

where w_k represents the entropy-derived weight of impact category k. Because the sum of the weights equals 1, no additional division by the number of indicators is required. A positive AER indicates an overall reduction in pollution-related environmental impacts relative to BAU, whereas a negative AER indicates an overall increase.

Table S8. Entropy weights of the 12 pollution-related environmental impact categories

Impact Category	Entropy (e_k)	Divergence (d_k)	Weight (w_k)	Weight (%)
TA	0.694918	0.305082	0.075305	7.53
FEC	0.665149	0.334851	0.082653	8.27
MEC	0.666877	0.333123	0.082226	8.22
TEC	0.732107	0.267893	0.066125	6.61
FEU	0.667896	0.332104	0.081975	8.20
MEU	0.787766	0.212234	0.052387	5.24
HCT	0.547639	0.452361	0.111658	11.17
HNT	0.665828	0.334172	0.082485	8.25
ODP	0.713888	0.286112	0.070622	7.06
PMF	0.712930	0.287070	0.070859	7.09
POF-HH	0.534061	0.465939	0.115010	11.50
POF-TE	0.559634	0.440366	0.108697	10.87

Note: The entropy-derived weights ranged from 5.24% for MEU to 11.50% for POF-HH. POF-HH, HCT, and POF-TE received relatively higher weights, whereas MEU and TEC received relatively lower weights, reflecting differences in the discriminatory information provided by individual impact categories across the four recycling routes.

Table S9. Entropy-weighted AER under different optimization scenarios

Scenario	Pyrometallurgy	Hydrometallurgy	Pyro-Hydrometallurgy	Direct Recycling
TPS	6.29%	8.03%	9.47%	9.54%
ETS	0.03%	5.56%	16.72%	5.63%
CS	6.32%	13.03%	24.51%	14.61%

NOTE: AER: the entropy-weighted average pollution-related reduction rate.

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