Supplementary Information (SI)

Surging Demand for Energy Storage Systems Exacerbates Lithium Supply Challenges in the Green Transition

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Method details.

Fleet module:

$$S^{\mathrm{V}}(t) = Pop(t) \times OW(t)$$
$$I^{\mathrm{V}}(t) = S^{\mathrm{V}}(t) - S^{\mathrm{V}}(t-1) + O^{\mathrm{V}}(t)$$
$$O^{\mathrm{V}}(t) = I^{\mathrm{V}}(t) \times L_{\mathrm{V}}(t,t')\mathrm{d}t$$
$$I_m^{\mathrm{V}}(t) = I^{\mathrm{V}}(t) \times MS_m^{\mathrm{V}}(t)$$
$$S_m^{\mathrm{V}}(t) = \int_{t_0}^{t} (I_m^{\mathrm{V}}(t) - O_m^{\mathrm{V}}(t))\,\mathrm{d}t$$

where $I^{\mathrm{V}}(t)$, $O^{\mathrm{V}}(t)$, and $S^{\mathrm{V}}(t)$ represent the total vehicle inflow, outflow, and stock, respectively; $I_m^{\mathrm{V}}(t)$, $O_m^{\mathrm{V}}(t)$,, and $S_m^{\mathrm{V}}(t)$ represent the inflow, outflow, and stock for each vehicle type m, respectively; $Pop(t)$ is the population; $OW(t)$ is the vehicle ownership; $MS_m^{\mathrm{V}}(t)$ is the market share for each vehicle type (powertrain) m; $L_{\mathrm{V}}(t,t')$ is the lifetime distribution for vehicle.

Vehicle-battery module:

$$S_m^{\mathrm{VB}}(t) = S_m^{\mathrm{V}}(t) \times BC_m(t)$$
$$I_m^{\mathrm{VB}}(t) = S_m^{\mathrm{VB}}(t) - S_m^{\mathrm{VB}}(t-1) + O_m^{\mathrm{VB}}(t)$$
$$O_m^{\mathrm{VB}}(t) = I_m^{\mathrm{VB}}(t) \times L_{\mathrm{VB}}(t,t')\mathrm{d}t$$
$$I_{m,n}^{\mathrm{VB}}(t) = I_m^{\mathrm{VB}}(t) \times MS_{m,n}^{\mathrm{VB}}(t)$$
$$S_{m,n}^{\mathrm{VB}}(t) = \int_{t_0}^{t} (I_{m,n}^{\mathrm{VB}}(t) - O_{m,n}^{\mathrm{VB}}(t))\,\mathrm{d}t$$

where $I_m^{\mathrm{VB}}(t)$, $O_m^{\mathrm{VB}}(t)$, and $S_m^{\mathrm{VB}}(t)$ represent the battery inflow, outflow, and stock for each vehicle type m, respectively; $I_{m,n}^{\mathrm{VB}}(t)$, $O_m^{\mathrm{VB}}(t)$, and $S_m^{\mathrm{VB}}(t)$ represent the battery inflow, outflow, and stock for each vehicle type m and battery chemistry n, respectively; $MS_{m,n}^{\mathrm{VB}}(t)$ is the market share for each battery chemistry n; $L_{\mathrm{VB}}(t,t')$ is the lifetime distribution for vehicle battery.

ESS module:

$$I^{\mathrm{ESS}}(t) = S^{\mathrm{ESS}}(t) - S^{\mathrm{ESS}}(t-1) + O^{\mathrm{ESS}}(t)$$
$$O^{\mathrm{ESS}}(t) = I^{\mathrm{ESS}}(t) \times L_{\mathrm{ESS}}(t,t')\mathrm{d}t$$
$$I_n^{\mathrm{ESS}}(t) = I^{\mathrm{ESS}}(t) \times MS_n^{\mathrm{ESSB}}(t)$$
$$S_n^{\mathrm{ESS}}(t) = \int_{t_0}^{t} (I_n^{\mathrm{ESS}}(t) - O_n^{\mathrm{ESS}}(t))\,\mathrm{d}t$$

where $I^{\mathrm{ESS}}(t)$, $O^{\mathrm{ESS}}(t)$, and $S^{\mathrm{ESS}}(t)$ is the total ESS battery inflow, outflow, and stock, respectively; $I_n^{\mathrm{ESS}}(t)$, $O_n^{\mathrm{ESS}}(t)$, and $S_n^{\mathrm{ESS}}(t)$ is the inflow, outflow, and stock for each battery chemistry n, respectively; $MS_n^{\mathrm{ESSB}}(t)$ is the market share for each battery chemistry n; $L_{\mathrm{ESS}}(t,t')$ is the lifetime distribution of ESS.

Material module:
In the non-cascading case:

$$I^{\mathrm{VBM}}(t) = \sum\nolimits_m \sum\nolimits_n I_{m,n}^{\mathrm{VB}}(t) \times LI_n$$
$$O^{\mathrm{VBM}}(t) = I^{\mathrm{VBM}}(t) \times\ L_{\mathrm{VB}}(t,t')\mathrm{d}t'$$

$$SS^{\mathrm{VBM}}(t) = O^{\mathrm{VBM}}(t) \times RR^{\mathrm{VB}}(t)$$
$$PS^{\mathrm{VBM}}(t) = I^{\mathrm{VBM}}(t) - SS^{\mathrm{VBM}}(t)$$

where $I^{\mathrm{VBM}}(t)$, $O^{\mathrm{VBM}}(t)$, $SS^{\mathrm{VBM}}(t)$, and $PS^{\mathrm{VBM}}(t)$ represent the lithium inflow (demand), outflow, secondary supply and primary supply requirement for EV in the non-cascading case, respectively; LI_n is the chemistry-specific lithium intensities, $RR^{\mathrm{VB}}(t)$ is the end-of-life recycling rate (EoL-RR) for EV batteries.

$$I^{\mathrm{ESSM}}(t) = \sum_n I_n^{\mathrm{ESS}}(t) \times LI_n$$
$$O^{\mathrm{ESSM}}(t) = I^{\mathrm{ESSM}}(t) \times \ L_{\mathrm{ESS}}(t, t')\mathrm{d}t'$$
$$SS^{\mathrm{ESSM}}(t) = O^{\mathrm{ESSM}}(t) \times RR^{\mathrm{ESS}}(t)$$
$$PS^{\mathrm{ESSM}}(t) = I^{\mathrm{ESSM}}(t) - SS^{\mathrm{ESSM}}(t)$$

where $I^{\mathrm{ESSM}}(t)$, $O^{\mathrm{ESSM}}(t)$, $SS^{\mathrm{ESSM}}(t)$, and $PS^{\mathrm{ESSM}}(t)$ denote lithium inflow (demand), outflow, secondary supply and primary supply requirement for ESS; $RR^{\mathrm{ESS}}(t)$represent the EoL-RR for ESS.

In the cascading case:

$$O^{\mathrm{VBM}'}(t) = I^{\mathrm{VBM}}(t) \times L_{\mathrm{VB}}(t, t')\mathrm{d}t' \times \left(1 - CU_n(t)\right)$$
$$SS^{\mathrm{VBM}'}(t) = O^{\mathrm{VBM}'}(t) \times RR^{\mathrm{VB}}(t)$$
$$PS^{\mathrm{VBM}'}(t) = I^{\mathrm{VBM}}(t) - SS^{\mathrm{VBM}'}(t)$$

where $O^{\mathrm{VBM}'}(t)$, $SS^{\mathrm{VBM}'}(t)$, and $PS^{\mathrm{VBM}'}(t)$ denote lithium outflow, secondary supply and primary supply requirement for EV under cascading case; $CU_n(t)$ is the cascading utilization rate for each EV battery chemistry n.

$$I^{\mathrm{ESSM}'}(t) = \sum_n [I_n^{\mathrm{ESS}}(t) - O_n^{\mathrm{VBM}}(t) \times CU_n(t)] \times LI_n$$
$$O^{\mathrm{ESSM}'}(t) = I^{\mathrm{ESSM}'}(t) \times L_{\mathrm{ESS}}(t, t')\mathrm{d}t' + O_n^{\mathrm{VBM}}(t) \times CU_n(t) L_{\mathrm{ESS}'}(t, t')\mathrm{d}t'$$
$$SS^{\mathrm{ESSM}'}(t) = O^{\mathrm{ESSM}'}(t) \times RR^{\mathrm{ESS}}(t)$$
$$PS^{\mathrm{ESSM}'}(t) = I^{\mathrm{ESSM}'}(t) - SS^{\mathrm{ESSM}'}(t)$$

where $I^{\mathrm{ESSM}'}(t)$, $O^{\mathrm{ESSM}'}(t)$, $SS^{\mathrm{ESSM}'}(t)$, and $PS^{\mathrm{ESSM}'}(t)$ denote lithium inflow (demand), outflow, secondary supply and primary supply requirement for ESS under cascading case; $L_{\mathrm{ESS}'}(t, t')$ is the lifetime distribution for cascading batteries.

Table S1. The parameters and assumptions for average product lifetime, end-of-life recycling rate (EoL-RR), second-use rate, and the loss rate of each process for lithium end-use sectors.

	Average product lifetime (Matos et al., 2020; Alves Dias et al., 2018) (Year)	End-of-life recycling rate (Weil and Ziemann, 2014) (%)	New scrap generation rate (Bailey et al., 2008; Graedel et al., 2011) (%)	New scrap recycling efficiency (Graedel et al., 2011) (%)	Manufacturing loss rate (Zeng et al., 2022; Ziemann et al., 2012) (%)	Refining loss rate (Guo et al., 2021) (%)	Mining loss rate (Guo et al., 2021) (%)
Battery-EV	8	0(before2010) 5(2010-2015) 30(after2015)	-	-	1	5	16.6
Battery-ESS	10	0(before2015) 30(after2015)	-	-	1		
Battery-CE	3	5(before2010) 10(after2010)	-	-	1		
Air conditions	10	1	-	-	1		
Aluminium welding and grazing, alloying, and production	2	0	40	76	12		
Ceramic and glass	30	0	-	-	1		
Lubricants and greases	10	0	-	-	1		
Primary battery (non-rechargeable battery)	1	0	-	-	1		
Polymer	2	0	-	-	1		
Others	5	0	-	-	1		

Table S2. The assumptions of key parameters for battery cathode technology scenarios for emerging end uses.

Parameters	Scenarios (by 2050)				
	BT1	BT2	BT3	BT4	BT5
Lithium intensity (kg/k Wh)	NMC-111/NMC-532:0.139; NMC-622: 0.126; NMC-811: 0.111; NCA: 0.112; LFP: 0.0943; Li-S: 0.168; Li-air: 0.075; SIB: 0; SSB: 0.095				
Battery cathode material market shares of EV	NCX-dominated	(LFP-dominated	LFP+SIB	LFP+SSB	LFP+Li-S/Air
	the cathode shares of the state-of-the-art technologies are assumed to shift from NMC-111towards NCA and NMC-811	LFP batteries penetrate the market from 3% in 2025 to 100% in 2050	Lithium-free sodium-based batteries (SIB) penetrate the market from zero in 2022 to 50% in 2050	Solid-state batteries (SSB) penetrate the market from zero in 2022 to 50% in 2050	Lithium-sulfur (Li-S) or lithium-air (Li-air) batteries penetrate the market from zero in 2022 to 50% in 2050
Battery cathode material of ESS	LFP-dominated	LFP-dominated	LFP+SIB	LFP+SSB	LFP-dominated
	LFP batteries penetrates the market from 40% in 2022 to 100% in 2050	LFP batteries penetrates the market from 40% in 2022 to 100% in 2050	Lithium free sodium-based batteries (SIB) gradually replace NMC batteries and dominate the market together with LFPs	Solid-state batteries (SSB) gradually replace NMC batteries and dominate the market together with LFPs	LFP batteries penetrates the market from 40% in 2022 to 100% in 2050

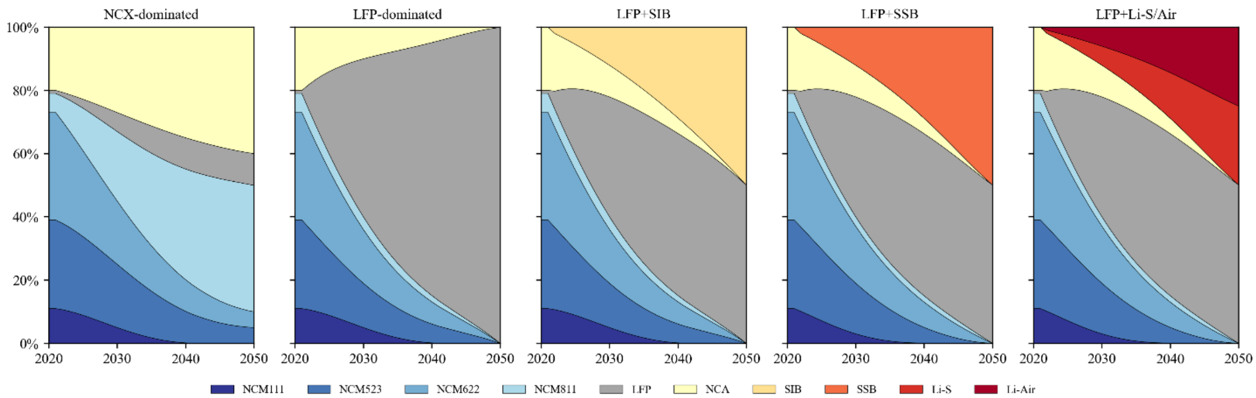

Fig. S1. Markey share of EV battery cathodes. (IRENA, 2024; Xu et al, 2020, 2023; Zeng et al., 2022; Zhang et al, 2023)

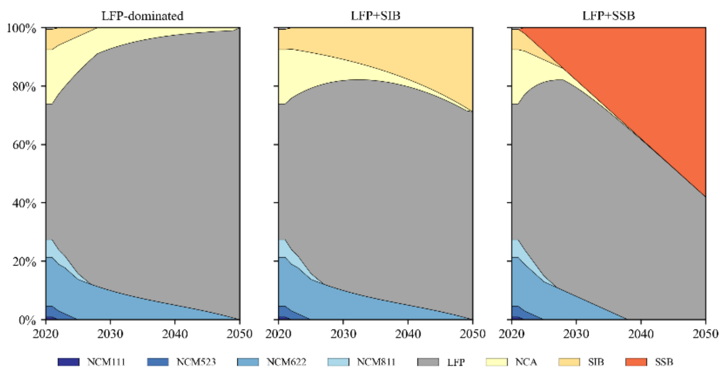

Fig. S2. Market share of ESS battery cathodes. (Xu et al, 2020, 2023; Zeng et al., 2022; Zhang et al, 2023)

Table S3. Battery lifetime scenarios for end uses.

Parameters	End uses	Scenarios (by 2050)	
		Base	**Extended**
Average battery lifetime	B-EV	8 years	16 years
	B-ESS	10 years	20 years

Table S4. Assumptions of recycling scenarios for all end uses.

Parameters	End uses	Scenarios (by 2050)	
		Base (Nansai et al., 2014; Xu et al., 2020)	**High**
Recycling rate	Battery-EV	60%	80%[a]
	Battery-ESS	60%	80%
	Battery-CE	20%[b]	40%
	Air conditions	2%	4%
	Aluminum alloy	0%	0%
	Ceramic and glass	1%	2%
	Lubricants and greases	0%	0%
	Pharmaceuticals and polymer	1%	2%
	Primary battery[d]	5%	10%
	Other[e]	0%	0%

Notes:

a. Due to difficulties in battery recycling technology development, we didn't double it in this scenario.

b. Battery recycling rates under tis category are low, mainly due to difficulty in collection.

c. The recycling rate for some end uses was 0% by 2021, we assume it increase to 1%, 2%, or 10% in different scenarios for non-expendable productions. The recycling rate remains 0% for process use and consumables.

d. Lithium recycling rates in the battery sector are expected to increase more significantly relative to other end uses, stemming from improvements in collection and recycling technologies.

e. This category includes catalysts for synthetic rubber production, sanitizing agents in food processing, and bottling industries, high performance aircraft components, and in swimming pools, and is considered in general to be a process use or consumable use.

Fig. S3. Prospective global lithium demand, primary supply capacity, and potential secondary supply under the EV-STEPS and ESS-STEPS demand scenario, 2020–2050.

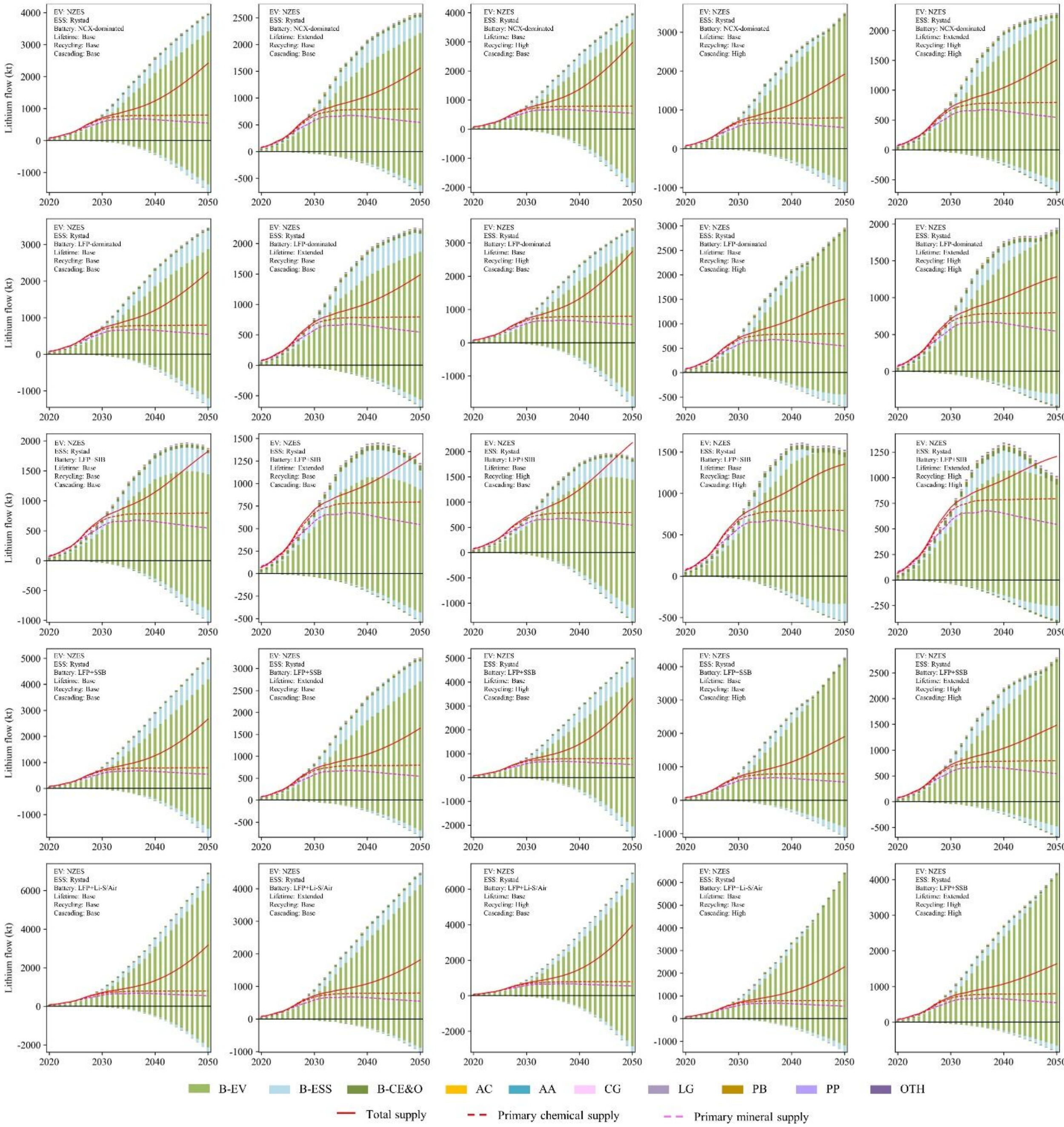

Fig. S4. Prospective global lithium demand, primary supply capacity, and potential secondary supply under the EV-NZES and ESS-NZES demand scenario, 2020–2050.

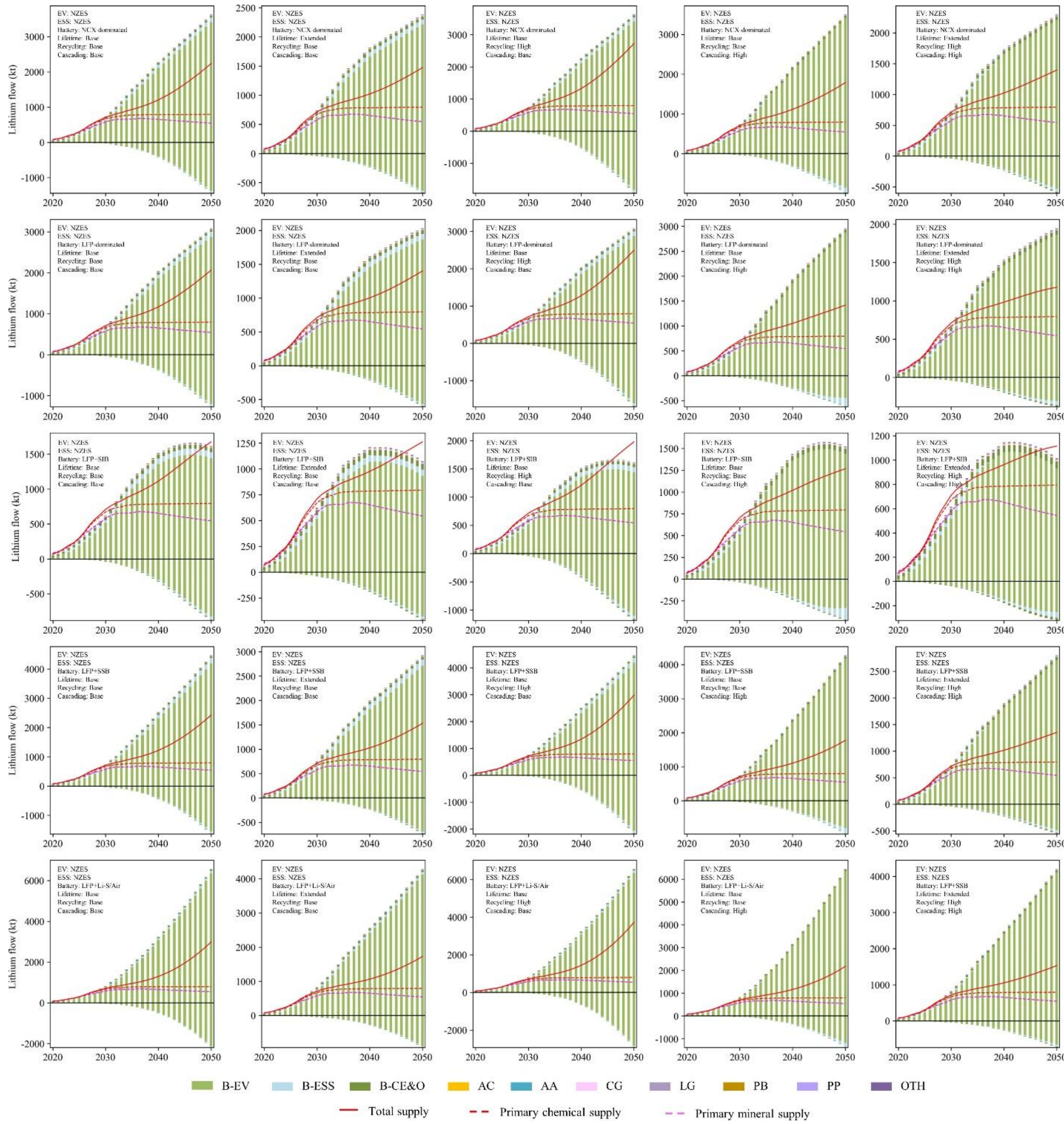

Fig. S5. Prospective global lithium demand, primary supply capacity, and potential secondary supply under the EV-NZES and ESS-Rystad demand scenario, 2020–2050.

References

Alves Dias P, Blagoeva D, Pavel C, Arvanitidis N (2018). Cobalt: demand-supply balances in the transition to electric mobility. Luxembourg: Publications of the European Commission.

Bailey R, Bras B, Allen J K (2008). Measuring material cycling in industrial systems. Resources, Conservation and Recycling, 52(4): 643–652

Graedel T E, Allwood J P, Reck B K, Sibley S F, Sonnemann G, Buchert M, Hagelüken C (2011). Recycling Rates of Metals: A Status Report. Report of the Working Group on the Global Metal Flows to the International Resource Panel. United Nations Environment Programme (UNEP)

Guo X, Zhang J, Tian Q (2021). Modeling the potential impact of future lithium recycling on lithium demand in China: a dynamic SFA approach. Renewable and Sustainable Energy Reviews, 137: 110461

International Renewable Energy Agency (IRENA) (2024). Batteries for Electric Vehicles: Critical Materials. Abu Dhabi: IRENA

Matos C T, Leon M F, Lundhaug M, Dewulf J, Müller D B, Georgitzikis K, Wittmer D, Mathieux F (2020). Material system analysis of five battery-related raw materials: cobalt, lithium, manganese, natural graphite, nickel. Luxembourg: Publications of the European Commission

Nansai K, Nakajima K, Kagawa S, Kondo Y, Suh S, Shigetomi Y, Oshita Y (2014). Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. Environmental Science & Technology, 48(3): 1391–1400

Weil M, Ziemann S (2014). Recycling of traction batteries as a challenge and chance for future lithium availability. In: Pistoia G, ed. Lithium-Ion Batteries. Amsterdam: Elsevier, 509–528

Xu C, Behrens P, Gasper P, Smith K, Hu M, Tukker A, Steubing B (2023). Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030. Nature Communications, 14: 119

Xu C, Dai Q, Gaines L, Hu M, Tukker A, Steubing B (2020). Future material demand for automotive lithium-based batteries. Communications Materials, 1: 99

Zeng A, Chen W, Rasmussen K D, Zhu X, Lundhaug M, Müller D B, Tan J, Keiding J K, Liu L, Dai T, Wang A, Liu G (2022). Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. Nature Communications, 13: 1341

Ziemann S, Weil M, Schebek L (2012). Tracing the fate of lithium – the development of a material flow model. Resources, Conservation and Recycling, 63: 26–34

Zhang C, Zhao X, Sacchi R, You F (2023). Trade-off between critical metal requirement and transportation decarbonization in automotive electrification. Nature Communications, 14: 1616