Supplementary Information

Future material demand for automotive lithium-based batteries

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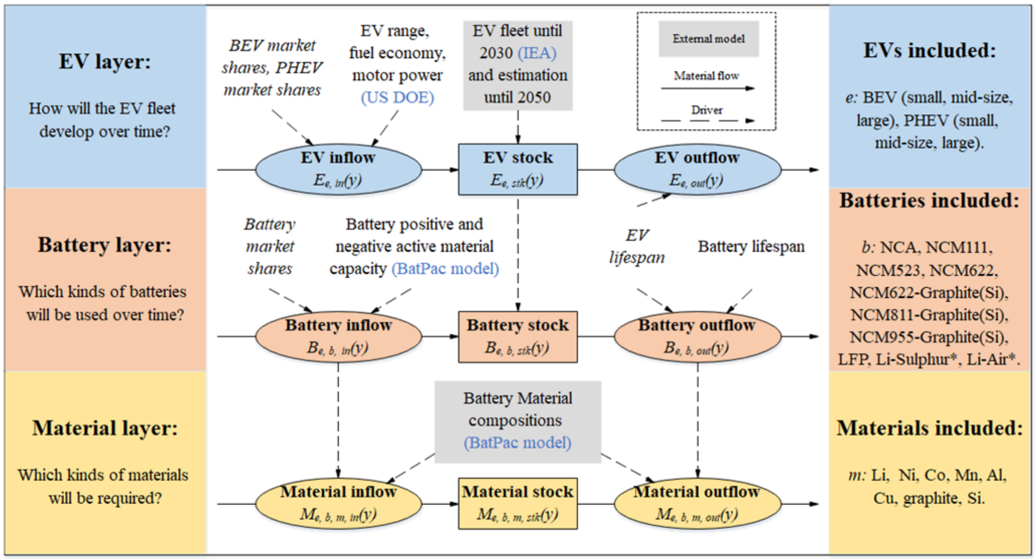
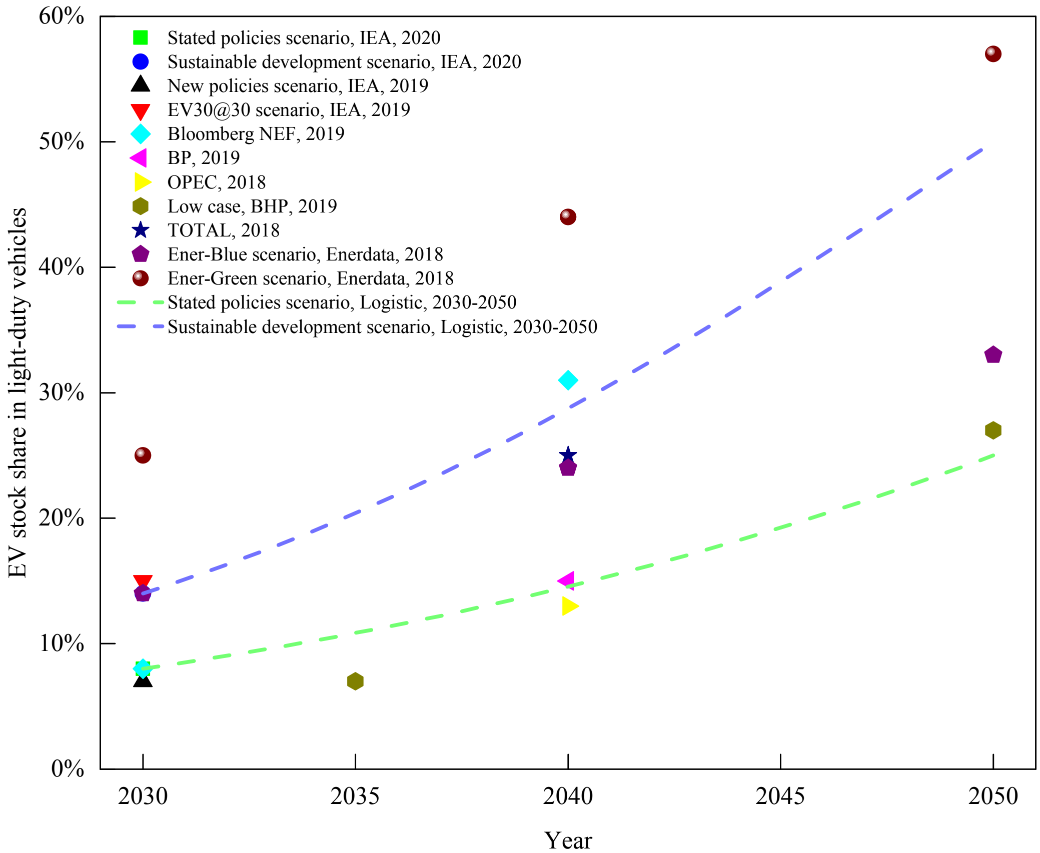
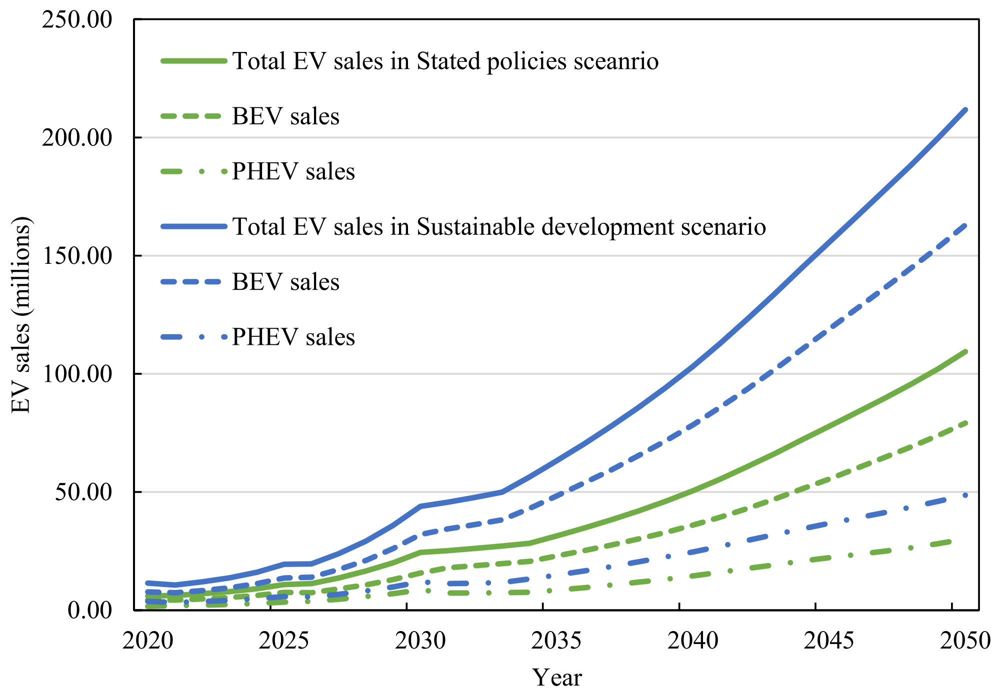
Supplementary Figures



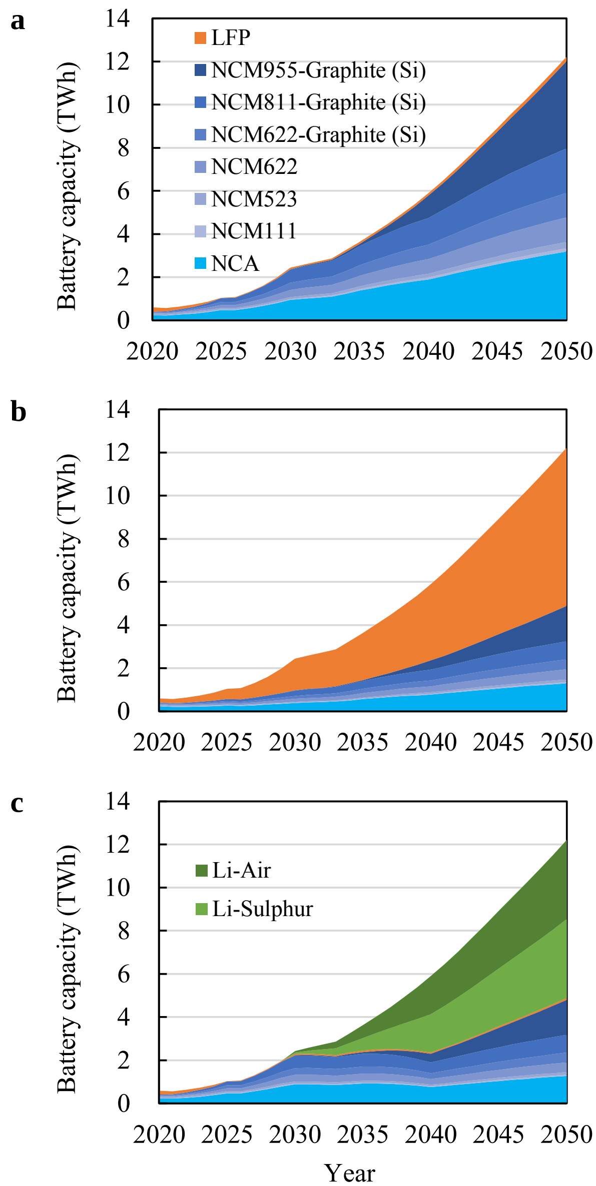
Supplementary Figure 1: Stock dynamics model on the EV, battery, and material layers: research questions (left), model structure (middle), and included categories (right). Driving factors are classified into predominantly technical and socio-economic (in italic) drivers. We use two EC fleet development scenarios until 2030 from International Energy Agency (IEA)[1]. The EV range, fuel economy, and motor power of various EV models are collected from the US DOE (US Department of Energy)[2]. The material compositions for various battery chemistries are calculated by using the BatPaC (Battery Performance and Cost) model from Argonne National Laboratory[3], expected for Li-Sulphur and Li-Air chemistries (marked with * as they are associated with uncertainty for EV applications[4]). Abbreviations: E, B, and M = EV, battery, and material; e, b, and m = categories of EV, battery, and material; In, stk, and out = inflow, stock, and outflow; y = year. See section of battery replacement and reuse for calculation equations.



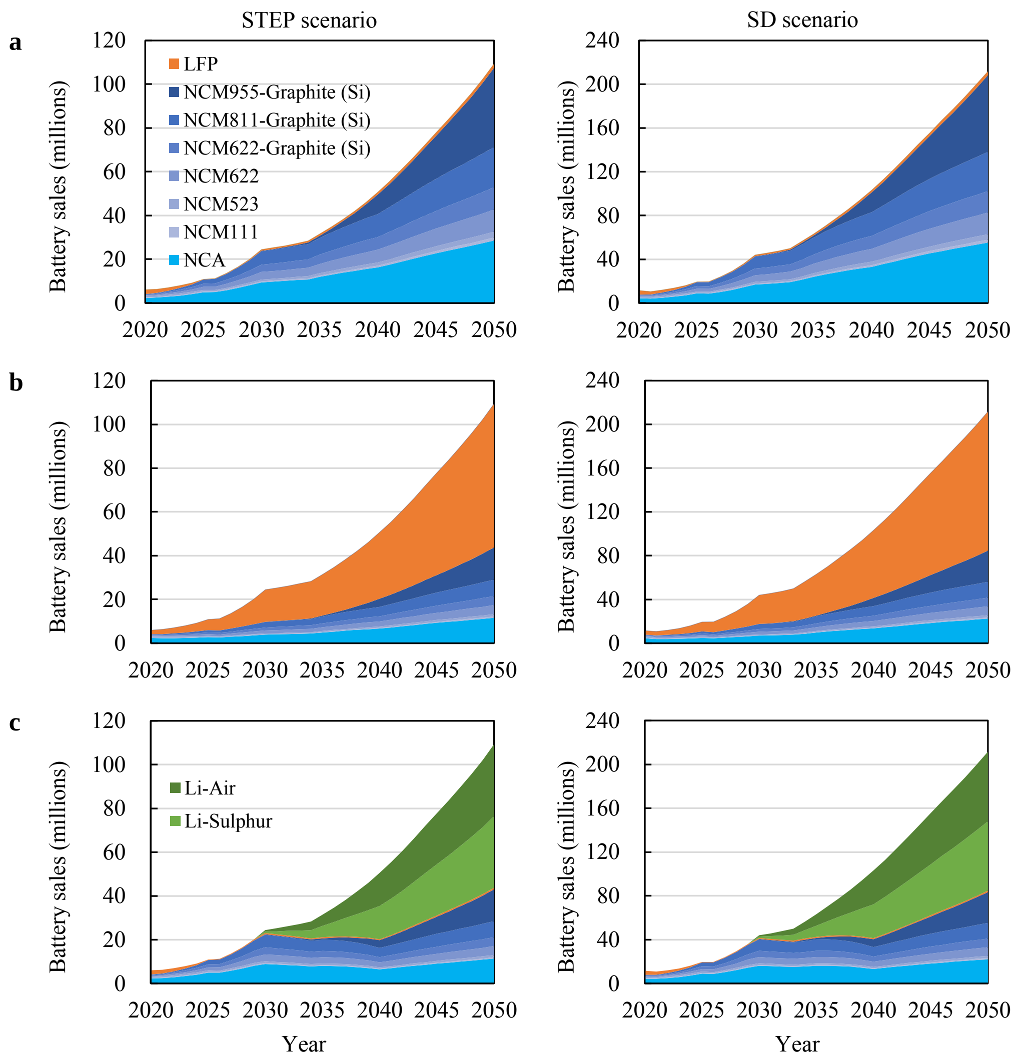
Supplementary Figure 2: Projections of EV stock share in light-duty vehicles from 2030 to 2050[1,5-11]. TOTAL projects 20%-30% of EV fleet share in 2040[9], which is shown as an average number of 25% in the figure. Green and blue dashed lines represent own estimations for the EV fleet share in the stated policies scenario and the sustainable development scenario of IEA[1] until 2050 by logistic model[12] respectively, which is comparable to other studies.



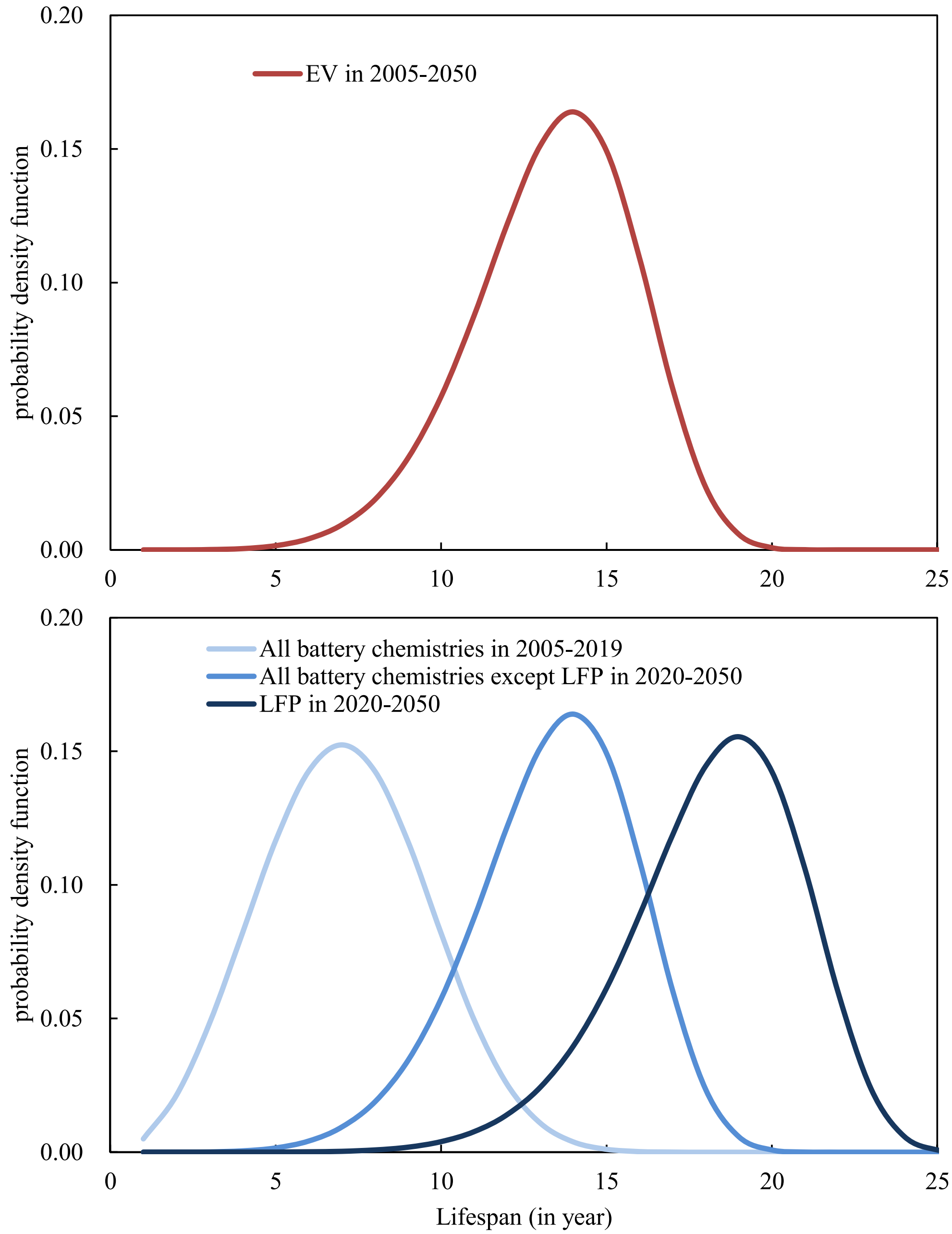
Supplementary Figure 3: Projections of global EV sales in the stated policies scenario and the sustainable development scenario in 2020-2050. EV sales are in rapid growth phase until 2050, based on the projections of EV stock share in light-duty passenger vehicles.



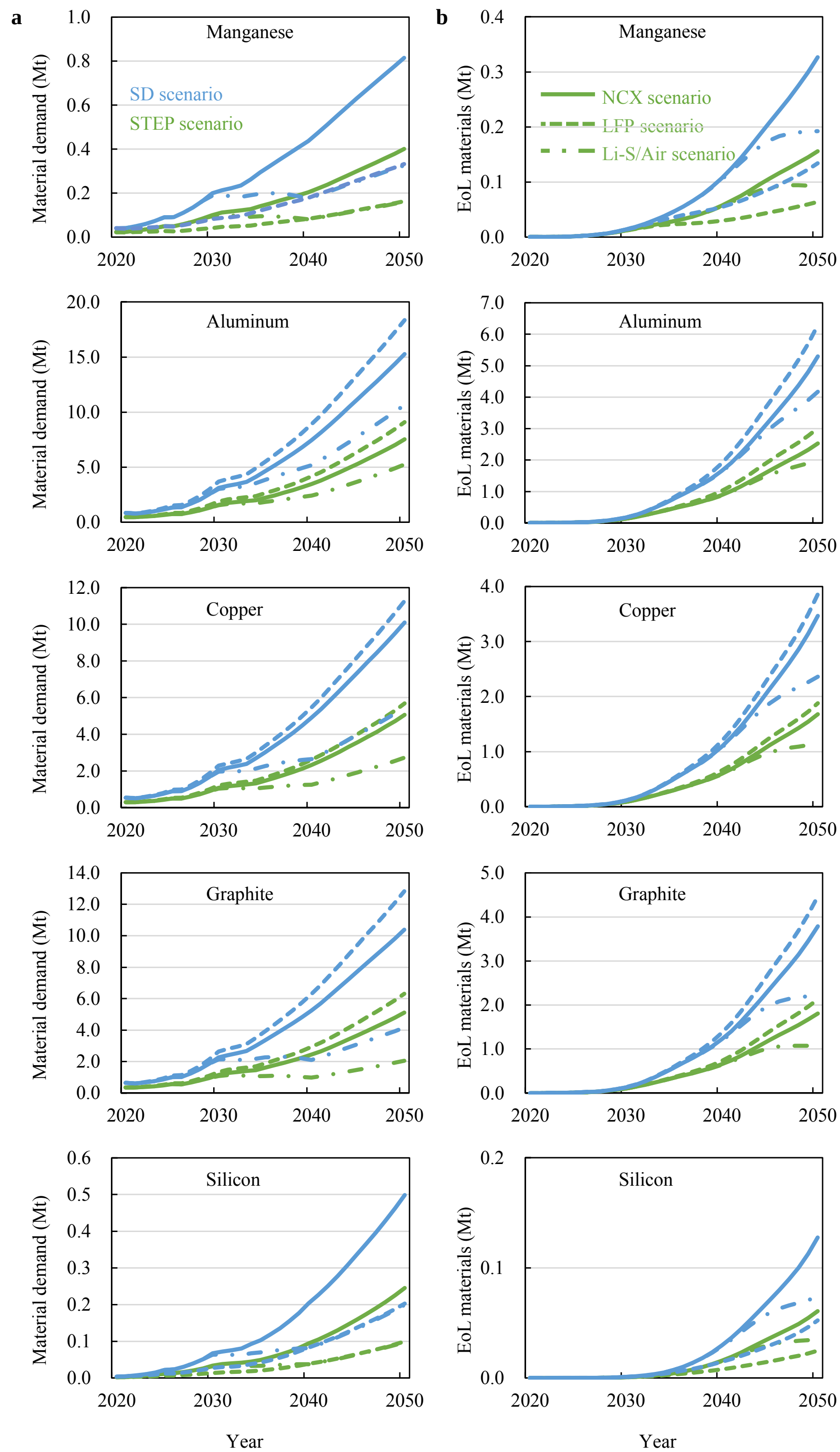
Supplementary Figure 4: EV battery sales by year in the NCX (a), LFP (b) and Li-S/Air (c) scenarios until 2050 for the fleet development of the SD scenario (unit: 1 TWh = 10^3 GWh = 10^6 MWh = 10^9 kWh).



Supplementary Figure 5: EV battery sales by year in the NCX (a), LFP (b) and Li-S/Air (c) scenarios until 2050 for the fleet development of the STEP scenario and the SD scenario (unit: millions).



Supplementary Figure 6: Weibull lifespan distributions of EVs and batteries.



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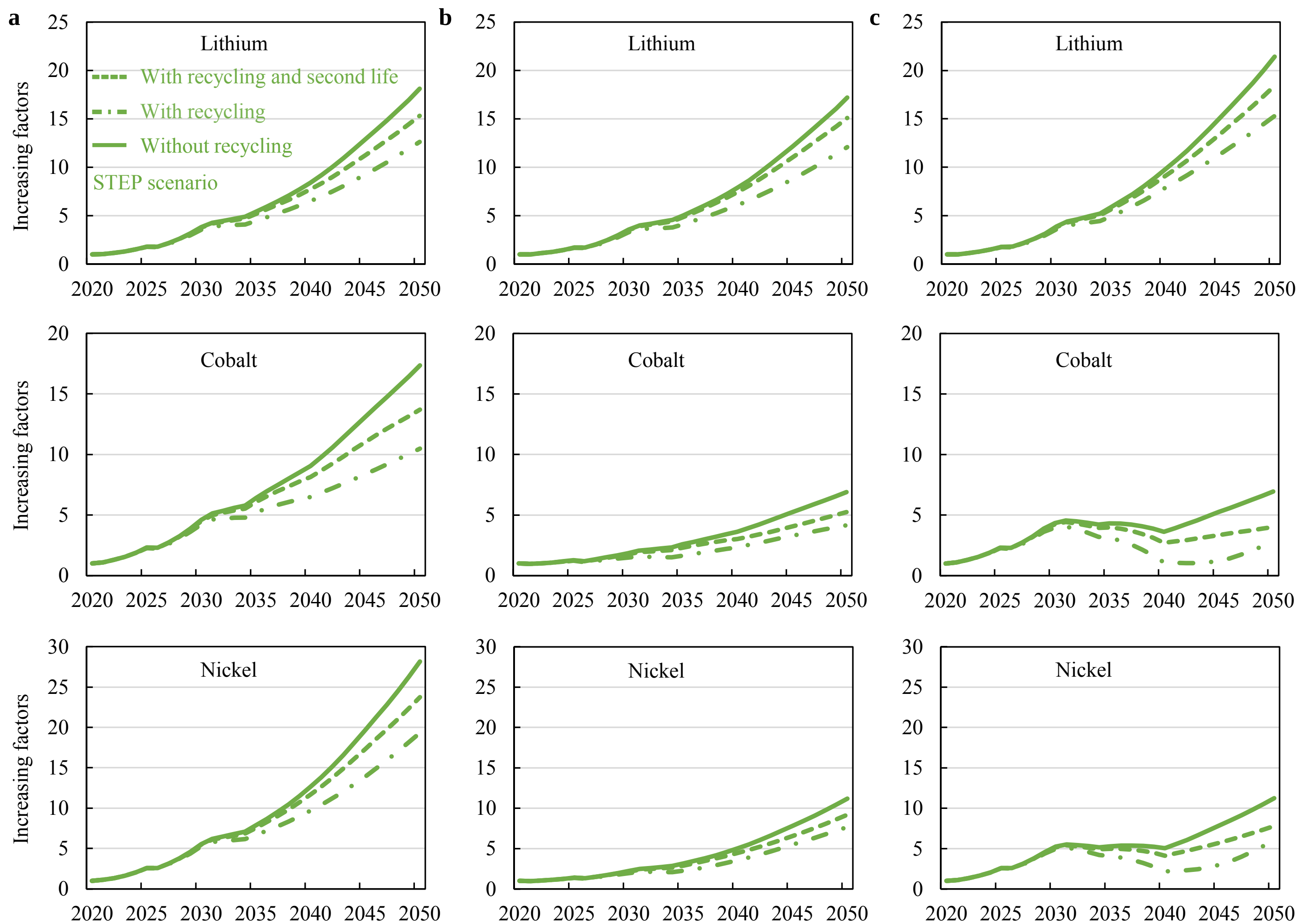
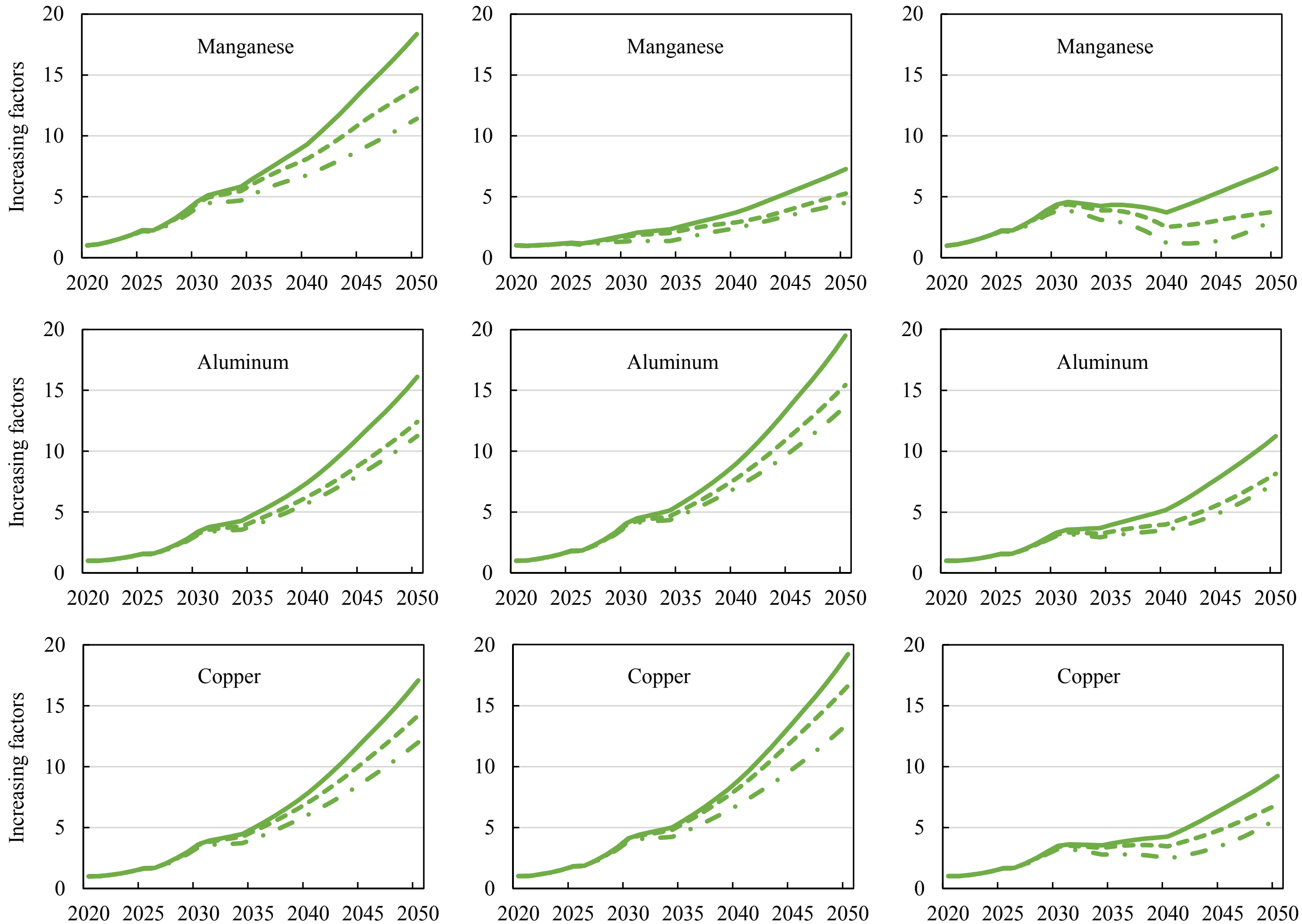
58 ***Supplementary Figure 7: Primary material demand (a) and materials in EoL batteries (b)***
59 ***from 2020 to 2050 for Mn, Al, Cu, graphite, and Si in the NCX, LFP and Li-S/Air battery***
60 ***scenarios. Mt = million tons.***



a
b
c
Lithium
Cobalt
Nickel
With recycling and second life
With recycling
Without recycling
STEP scenario
Increasing factors
2020 2025 2030 2035 2040 2045 2050


Manganese
Manganese
Manganese
Aluminum
Aluminum
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Copper
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Increasing factors
Increasing factors
Increasing factors
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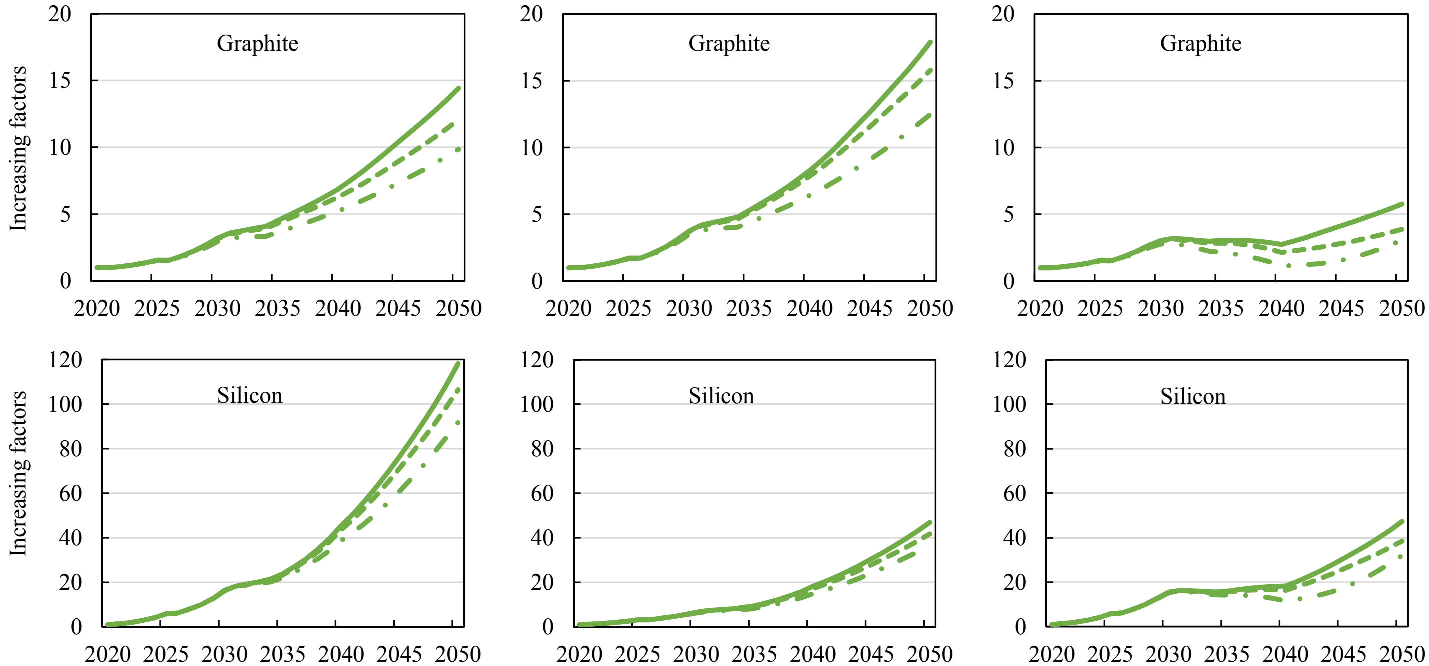
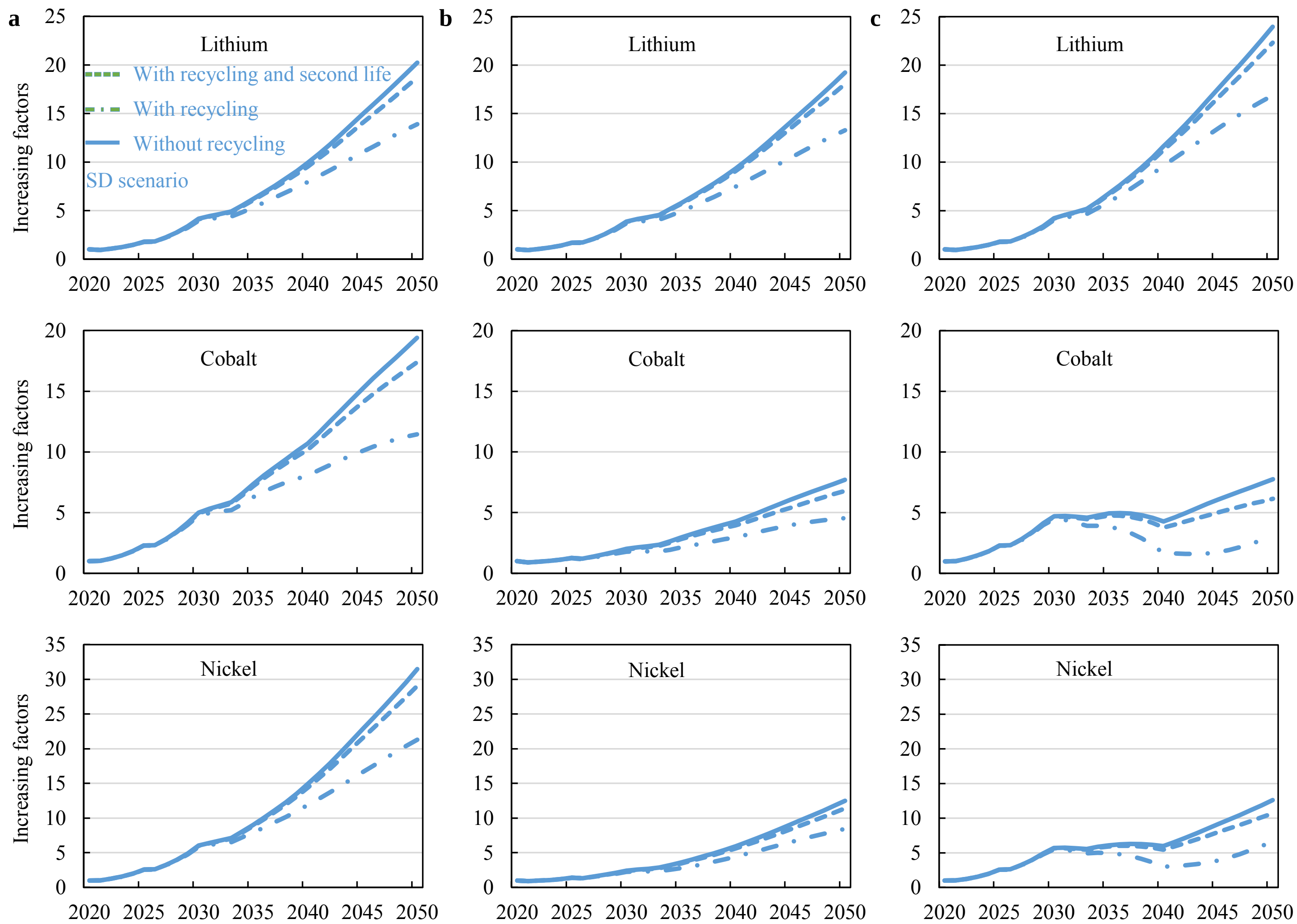
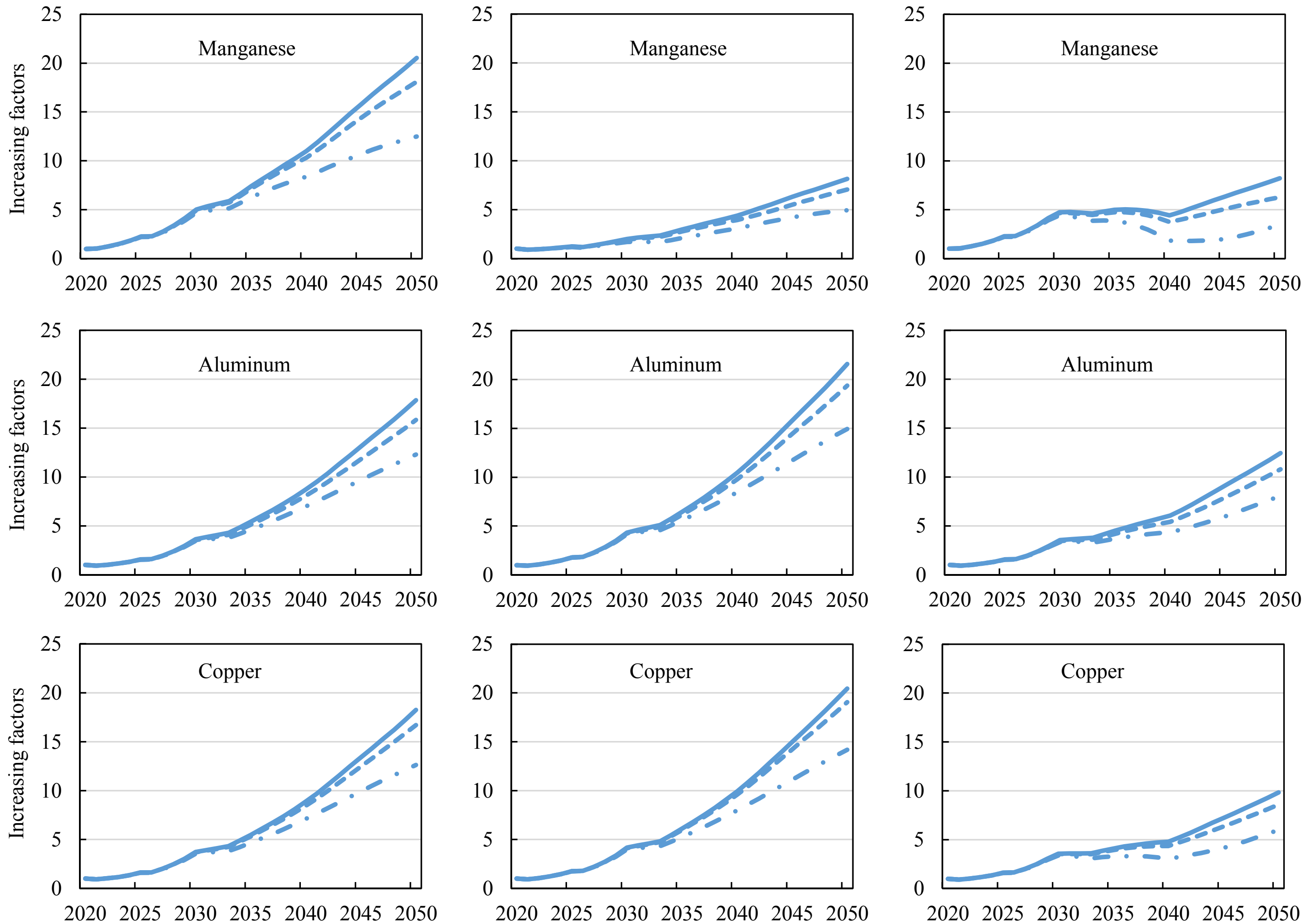


Supplementary Figure 8: Increasing factors for the primary demand for Li, Ni, Co, Mn, Al, Cu, graphite, and Si from 2020 to 2050 in the STEP scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios. Here recycling refers to hydrometallurgical recycling as an example.


a
b
c
Lithium
Cobalt
Nickel
With recycling and second life
With recycling
Without recycling
SD scenario
Increasing factors
2020 2025 2030 2035 2040 2045 2050


Manganese
Manganese
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Aluminum
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Copper
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Increasing factors
Increasing factors
Increasing factors
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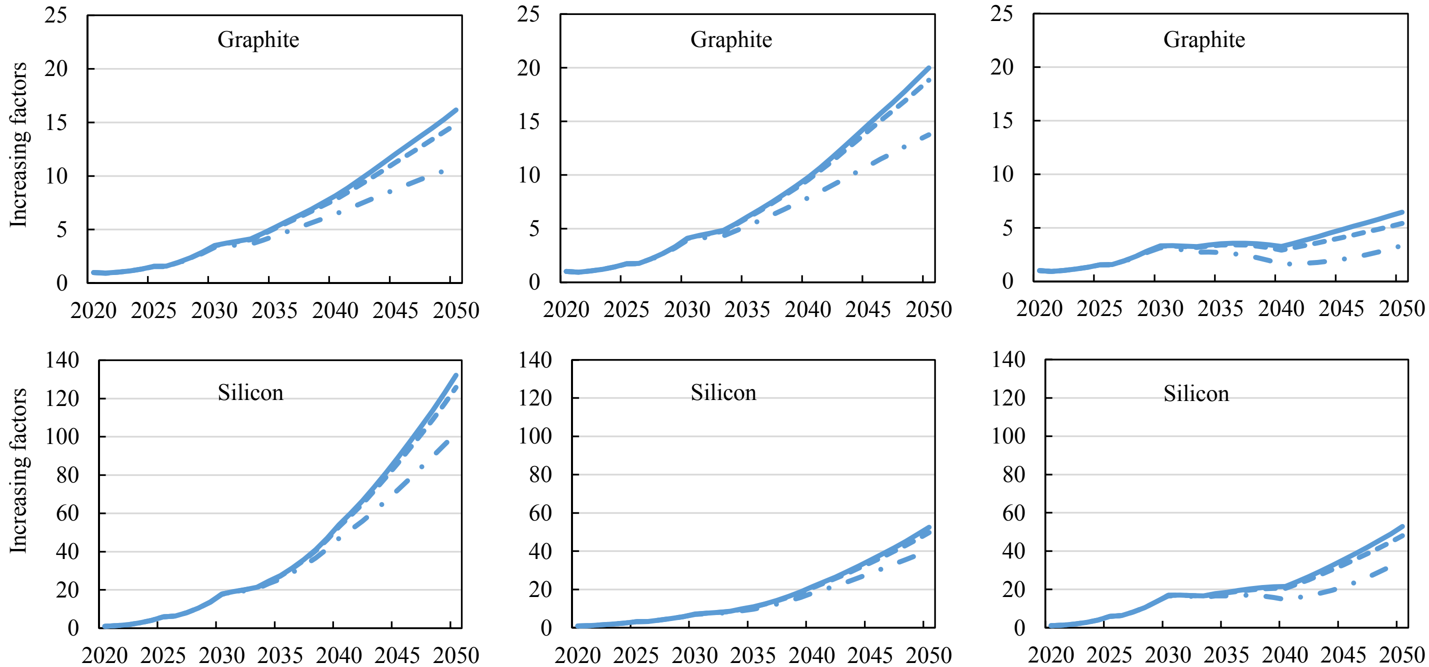
2020 2025 2030 2035 2040 2045 2050



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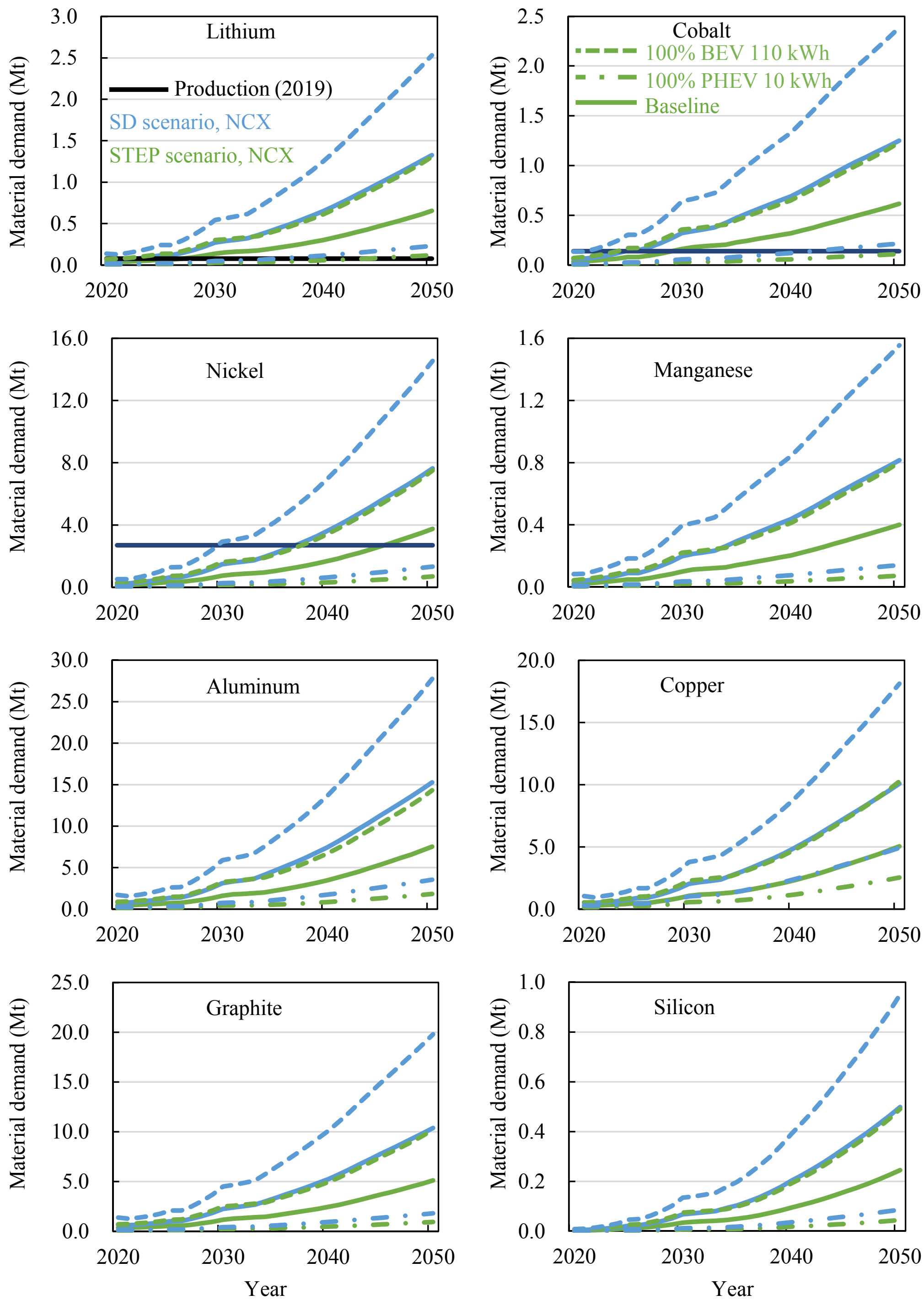
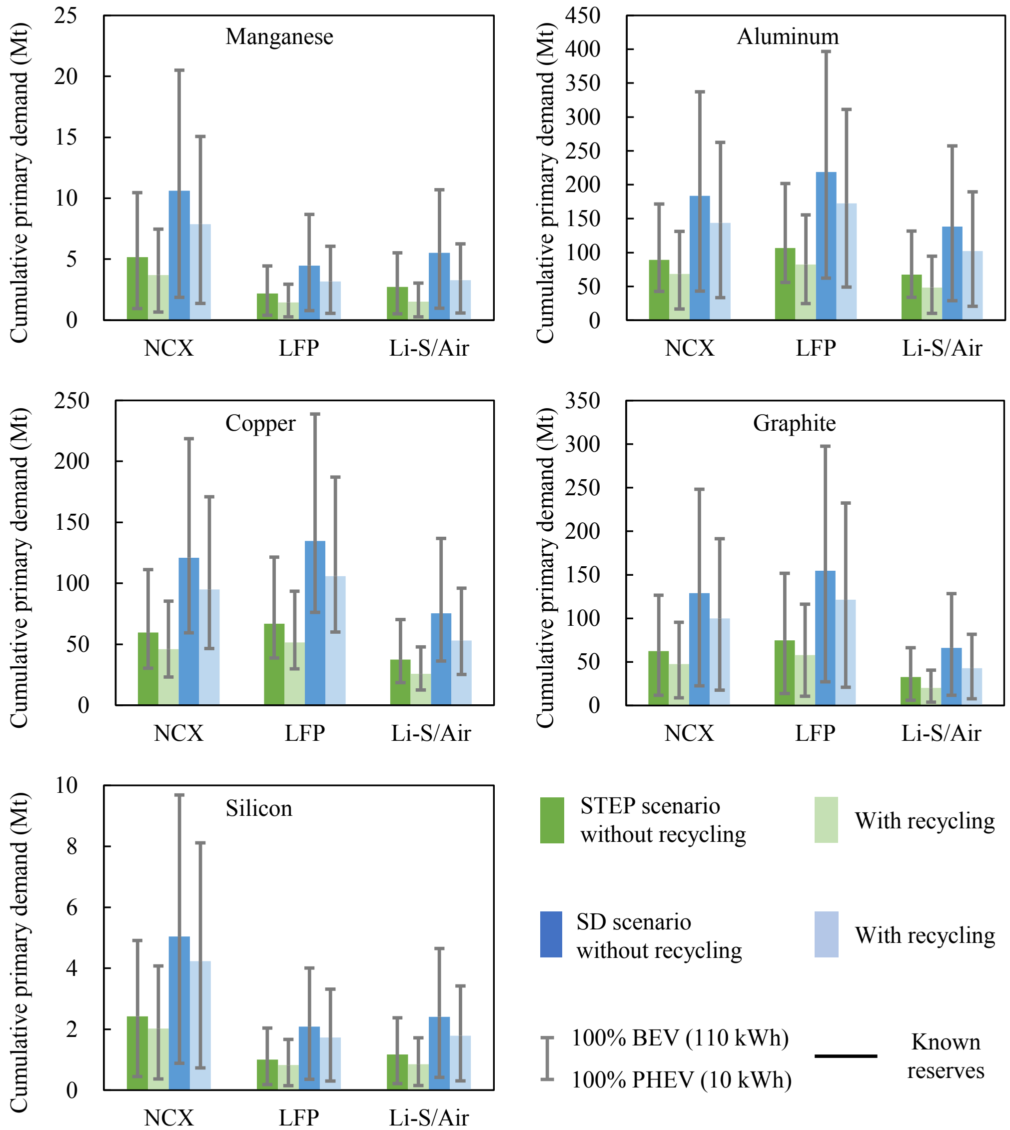
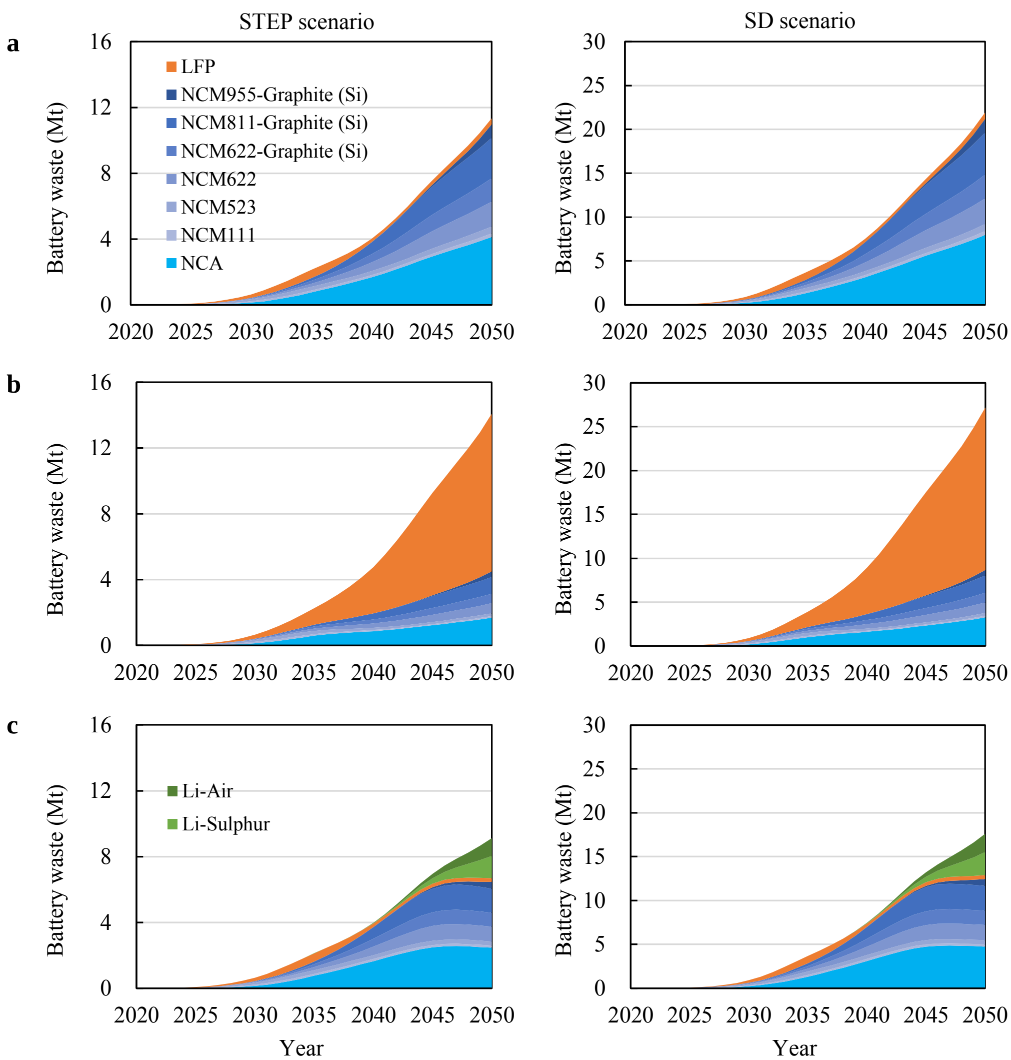
70 ***Supplementary Figure 9: Increasing factors for the primary demand of Li, Ni, Co, Mn, Al, Cu, graphite, and Si from 2020 to 2050 in the SD scenario in***
71 ***the NCX (a), LFP (b) and Li-S/Air (c) scenarios. Here recycling refers to hydrometallurgical recycling as an example.***



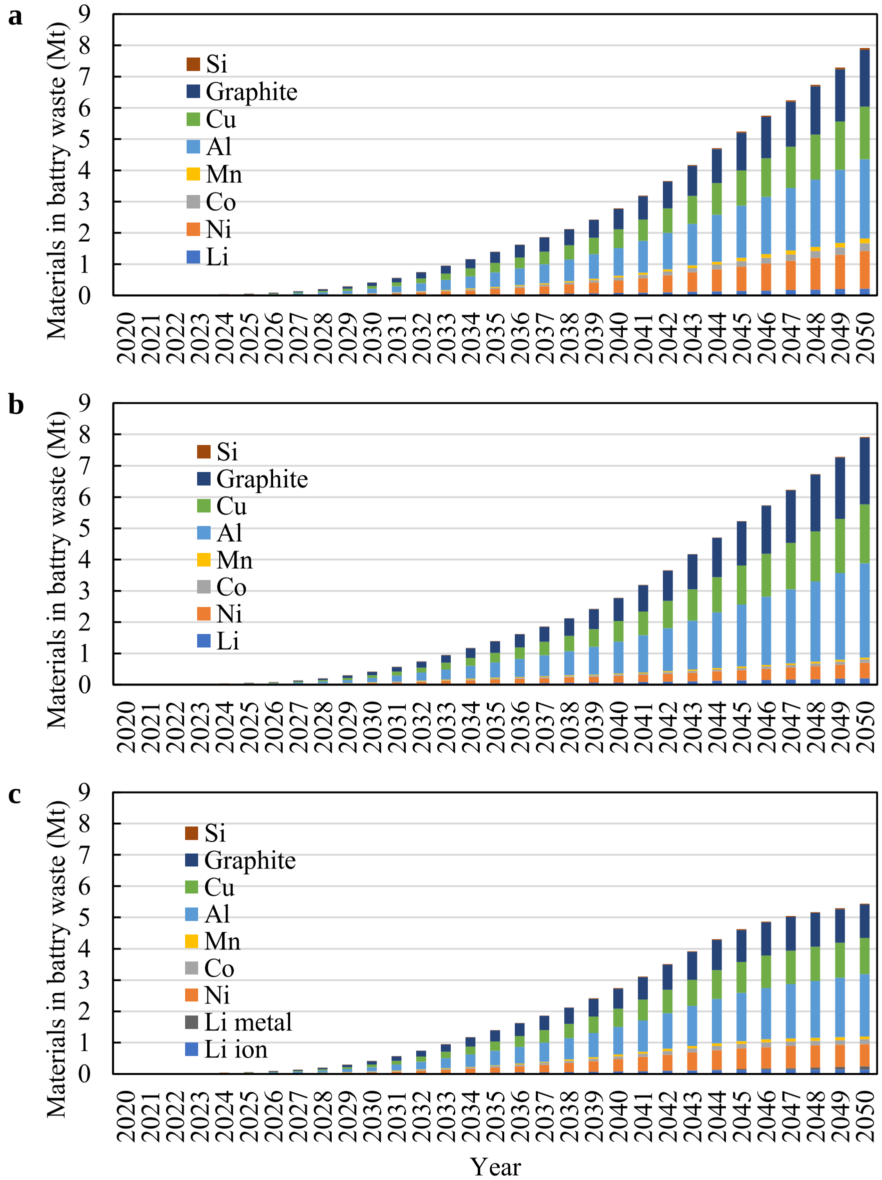
Supplementary Figure 10: Result of sensitivity analysis of required battery capacity (i.e. 100% BEV with 110 kWh and 100% PHEV with 10 kWh) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



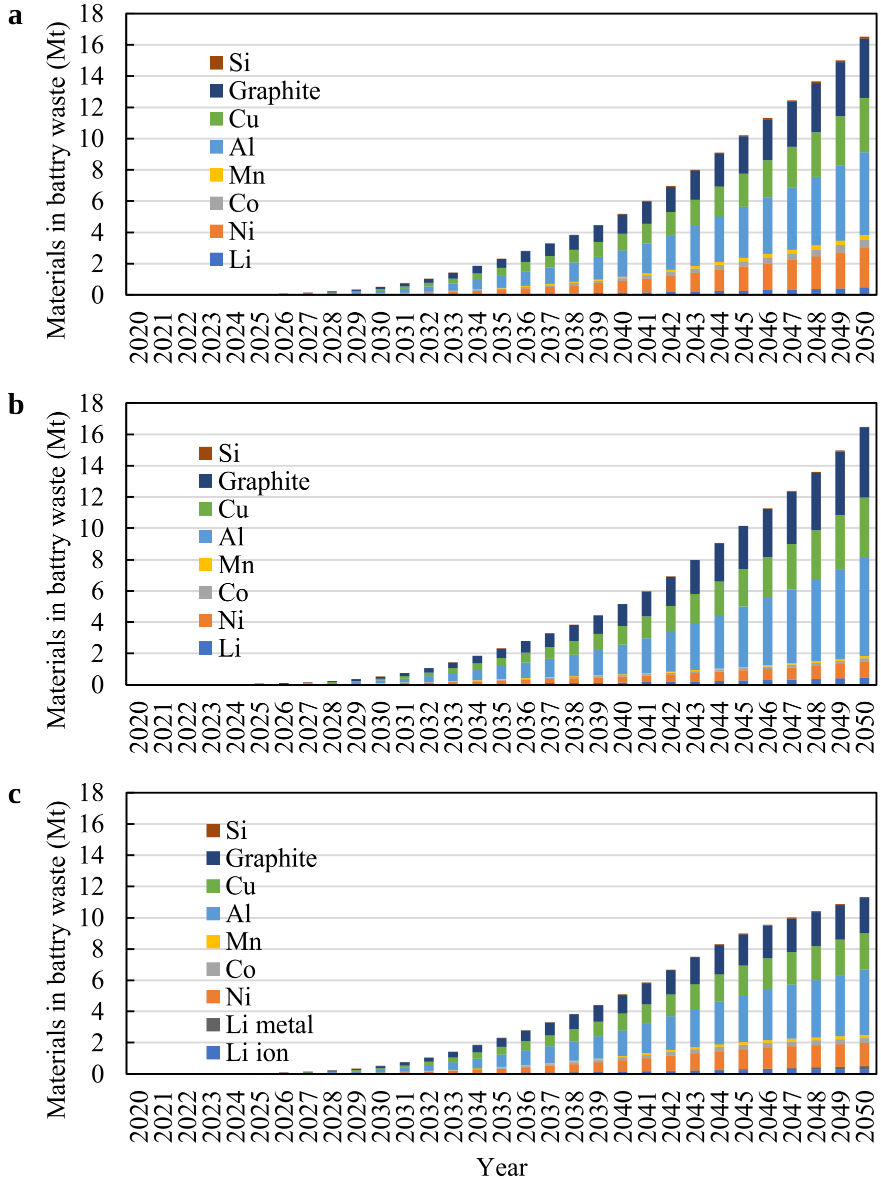
Supplementary Figure 11: Cumulative primary demand for Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling or with hydrometallurgical recycling. Grey error bars represent a sensitivity analysis for battery capacity considering two extreme cases (if all EVs were PHEVs with small 10 kWh batteries or if all EVs were large SUVs with 110 kWh batteries, e.g. Tesla's Model S Long Range Plus[13]). The global known reserves in 2019 for Mn, Al, Cu, graphite, and Si are shown in Supplementary Table 5, which are much higher than cumulative primary material demand from EV batteries only.



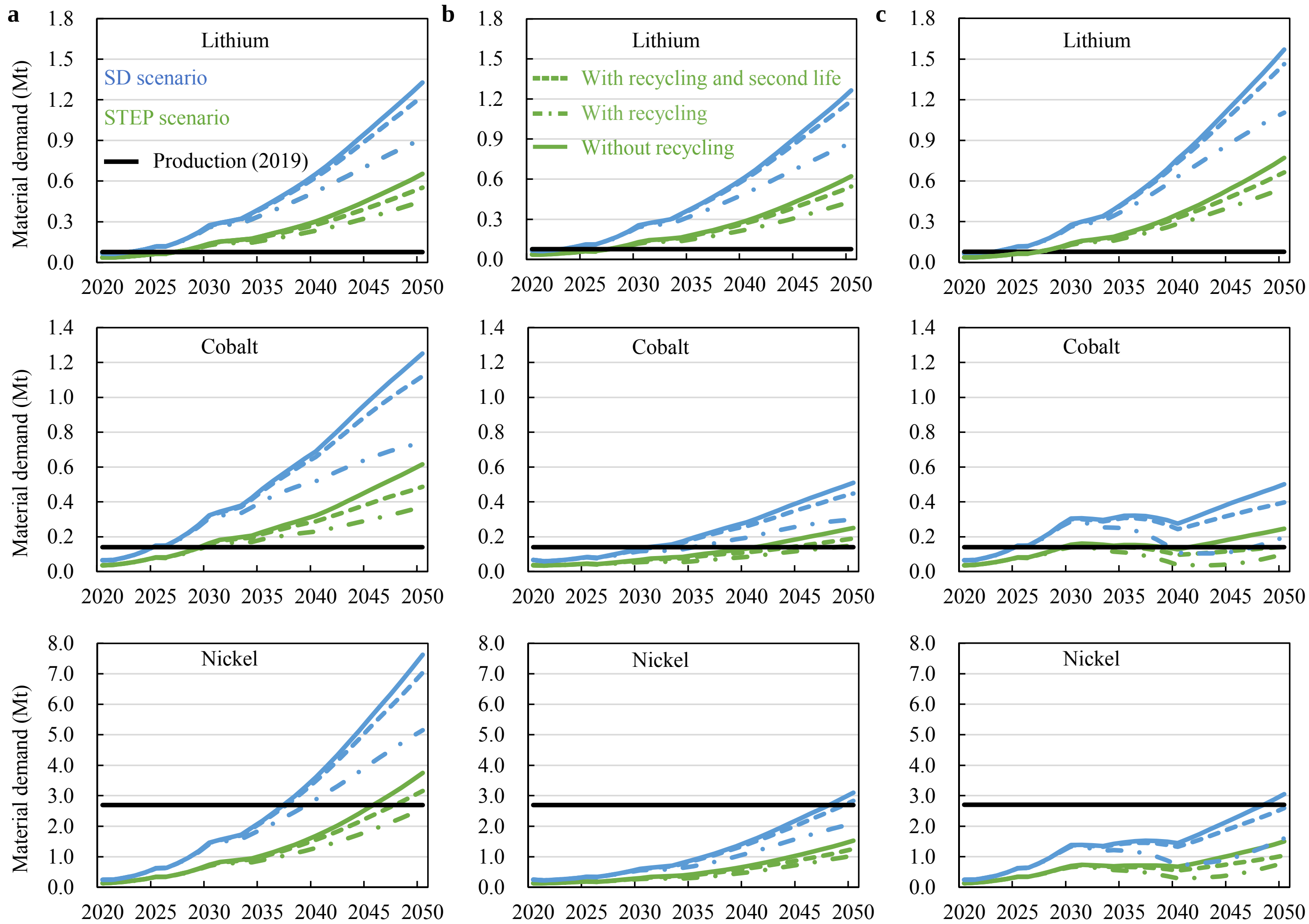
Supplementary Figure 12: Future battery waste stream by chemistry in the NCX (a), LFP (b) and Li-S/Air (c) scenarios until 2050 (unit: Mt = million tons). Under the STEP scenario, the EV battery waste stream reach around 11 Mt in 2050 if NCX scenario is realized, which is lower than the LFP scenario (14 Mt) and higher than the Li-S/Air scenario (9 Mt). The differences among three battery chemistry scenarios are associated with the relatively lower specific energy of LFP chemistry and higher specific energy of Li-S and Li-Air chemistries compared to NCA and NCM series chemistries. Driven by higher EV fleet deployments, the weight of EV battery waste stream reaches around 2 times in the SD scenario than the STEP scenario.



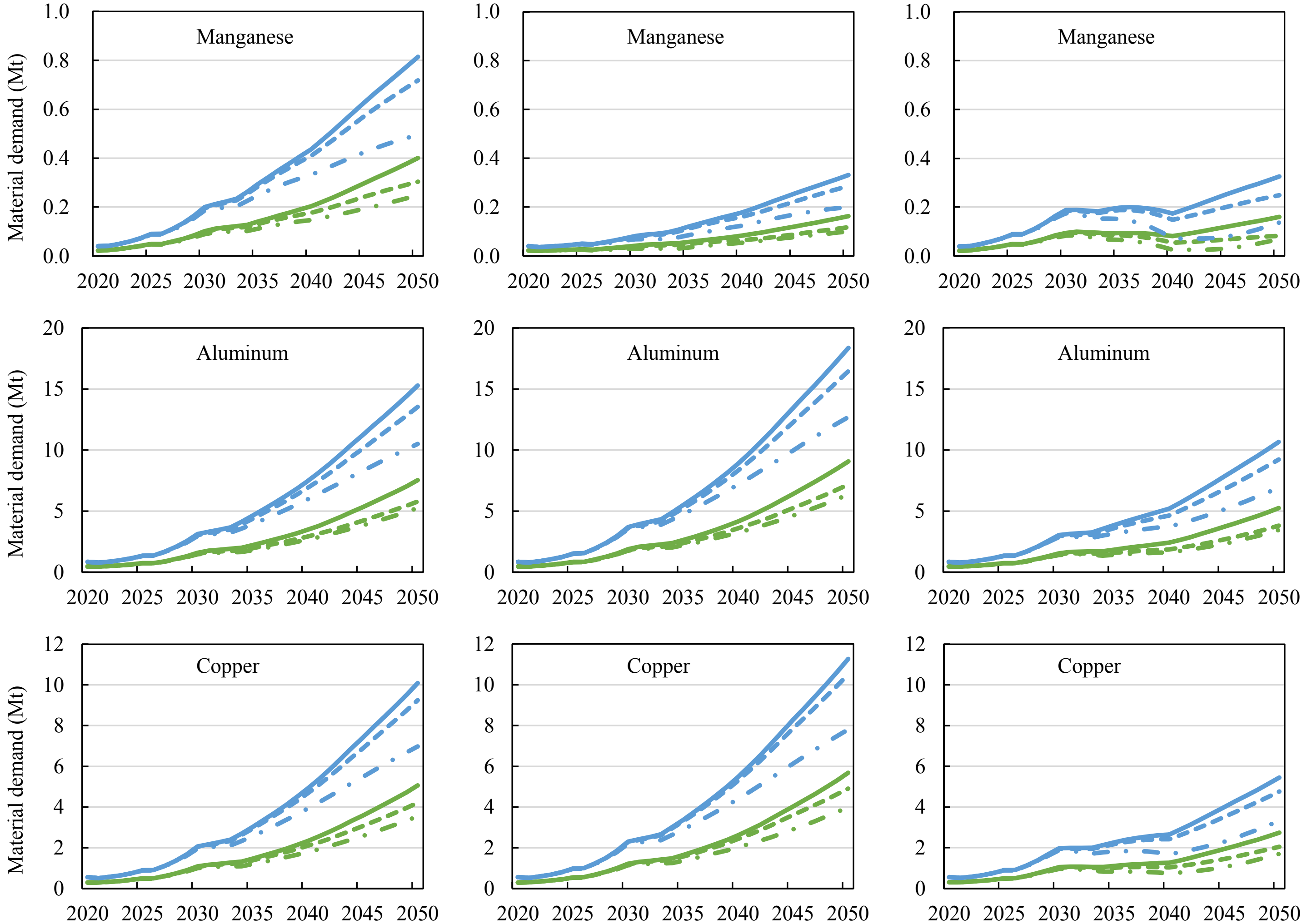
Supplementary Figure 13: Materials in future EV battery waste steam potentially available for recycling without second life use until 2050 in the STEP scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios (unit: Mt = million tons). The total weight of eight EoL materials in 2050 in the NCX scenario is almost equal to the LFP scenario, but with different material shares, especially for the EoL Ni weight in the NCX scenario is much higher than the LFP scenario. The total weight of eight EoL materials in the Li-S/Air scenario (Li includes Li ion in lithium chemical compounds and Li metal) is much lower than the other two battery scenarios, however, EoL Li weight is slightly higher.

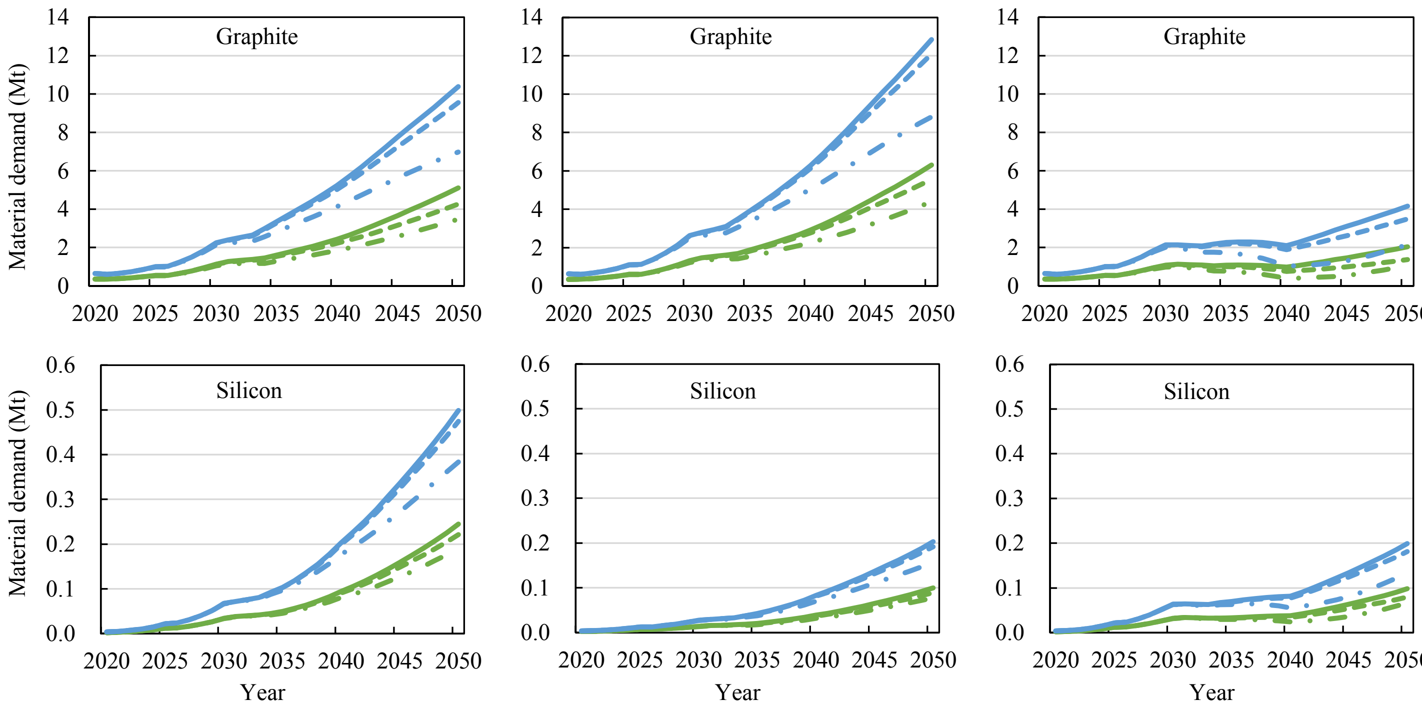


Supplementary Figure 14: Materials in future EV battery waste steam potentially available for recycling without second life use until 2050 in the SD scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios (unit: Mt = million tons). We can see the same pattern for EoL materials in the SD scenario as the STEP scenario. However, the weight of EoL materials available for recycling in the SD scenario is around 2 times than the STEP scenario.

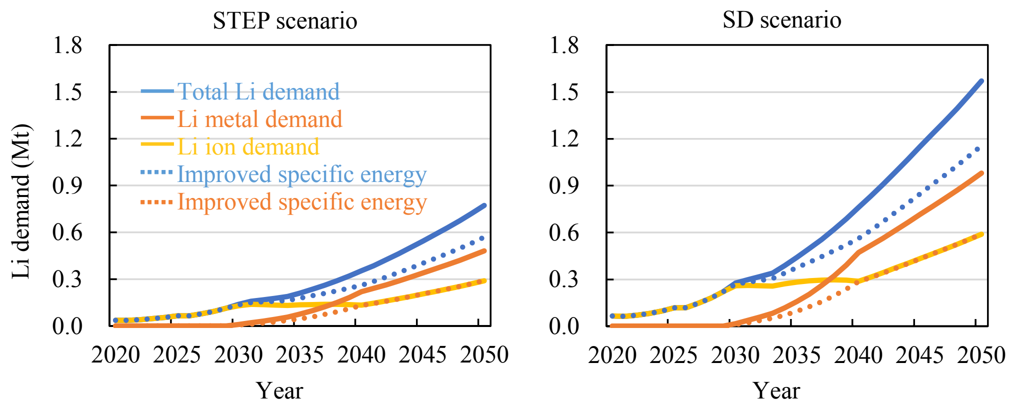

a
b
c
Lithium
Cobalt
Nickel
SD scenario
STEP scenario
Production (2019)
With recycling and second life
With recycling
Without recycling
Material demand (Mt)
2020 2025 2030 2035 2040 2045 2050

113

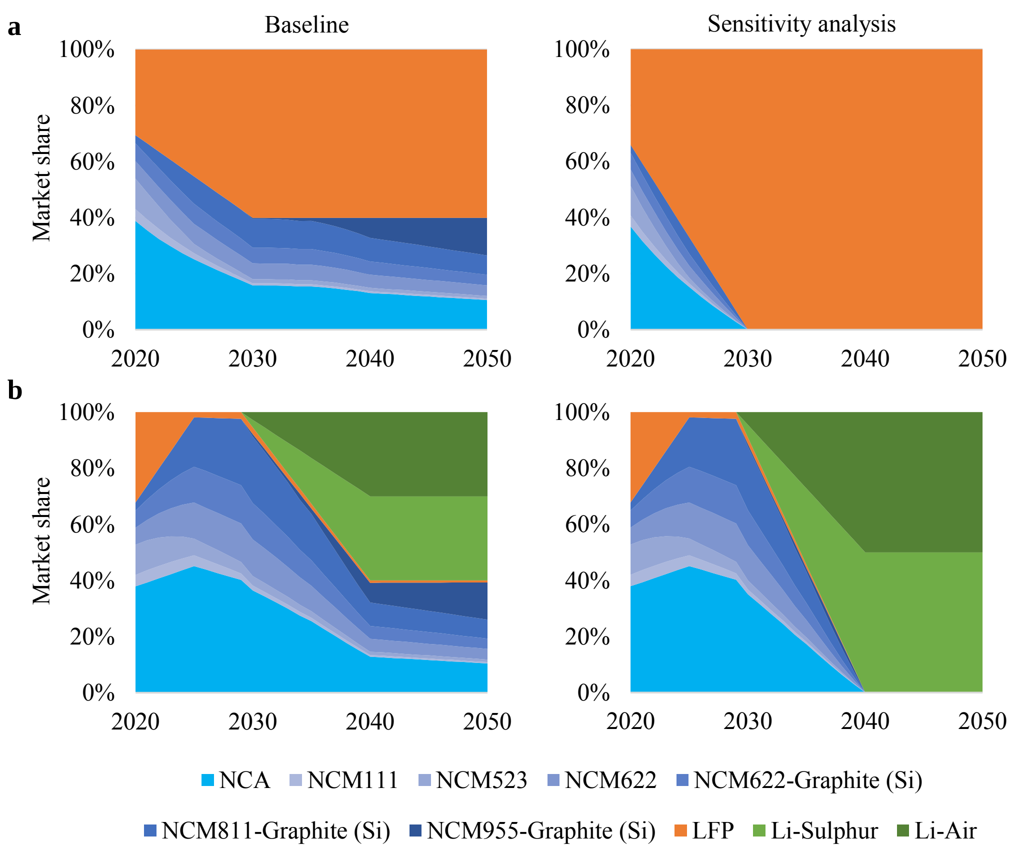

Manganese
Manganese
Manganese
Aluminum
Aluminum
Aluminum
Copper
Copper
Copper
Material demand (Mt)
Material demand (Mt)
Material demand (Mt)
0.0 0.2 0.4 0.6 0.8 1.0
0 5 10 15 20
0 2 4 6 8 10 12
2020 2025 2030 2035 2040 2045 2050



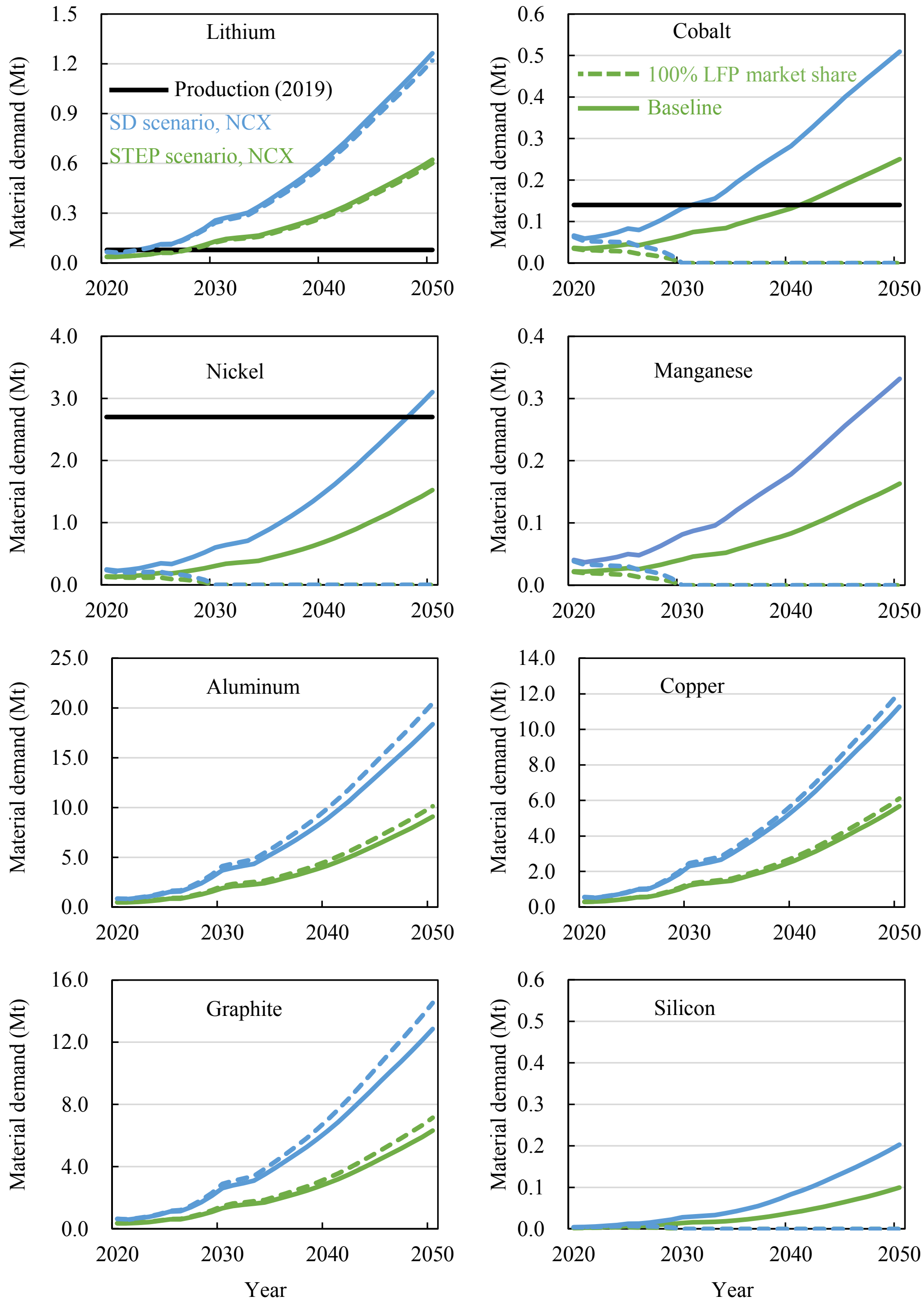
Supplementary Figure 15: Primary battery material demand in the NCX (a), LFP (b) and Li-S/Air (c) scenarios from 2020 to 2050 without recycling, with recycling, and with recycling and second life. Here recycling refers to hydrometallurgical recycling as an example.



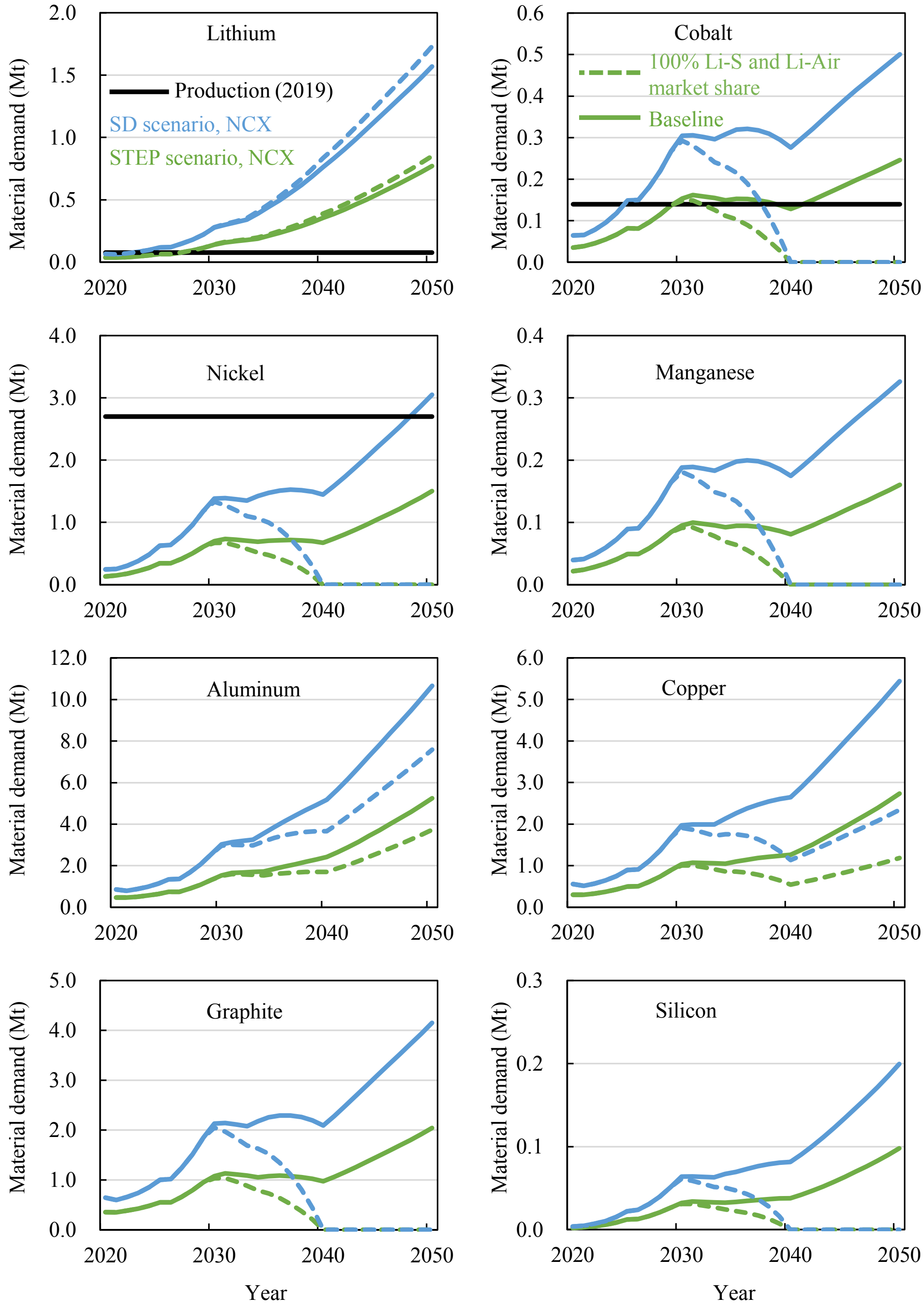
Supplementary Figure 16: Lithium demand split by Li ion (in the form of chemicals like Li_2CO_3, LiOH, etc.) and Li metal (in Li anode of Li-S and Li-Air chemistries) in the Li-S/Air scenario, including a sensitivity analysis for improved specific energy of Li-S and Li-Air chemistries. Based on reviewing of the specific energy of Li-S and Li-Air cells from lab and commercial scales (see Supplementary Tables 21 and 22), the specific energy of Li-S cells is improved from 400 Wh/kg to 600 Wh/kg, and the specific energy of Li-Air cells from 500 Wh/kg to 1000 Wh/kg. Specific energy improvements of Li-S and Li-Air cells can make total Li demand in the Li-S/Air scenario lower than LFP and NCX scenarios.



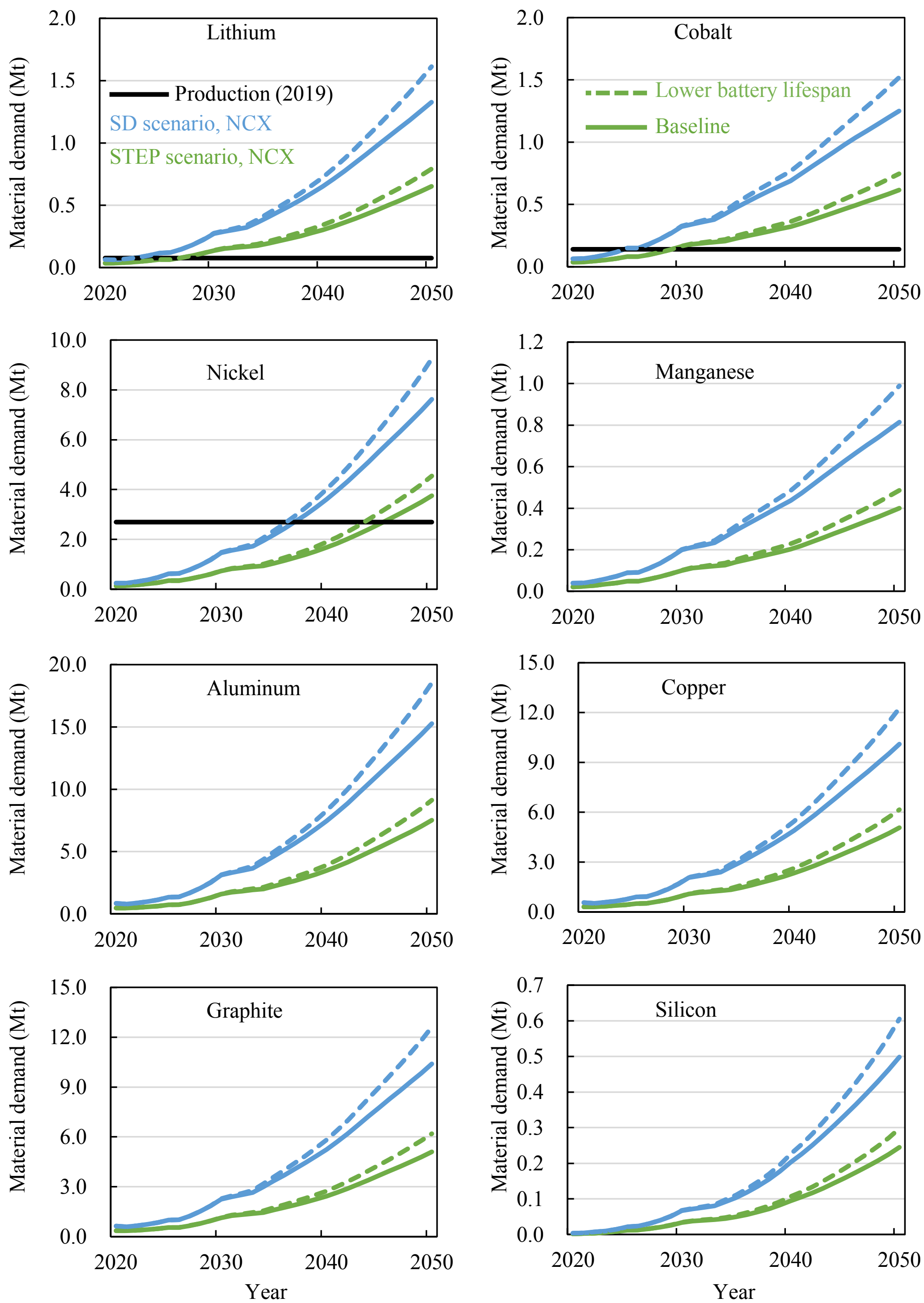
Supplementary Figure 17: Input of sensitivity analysis of LFP market share in the LFP scenario (a) and Li-S and Li-Air market shares in the Li-S/Air scenario (b).



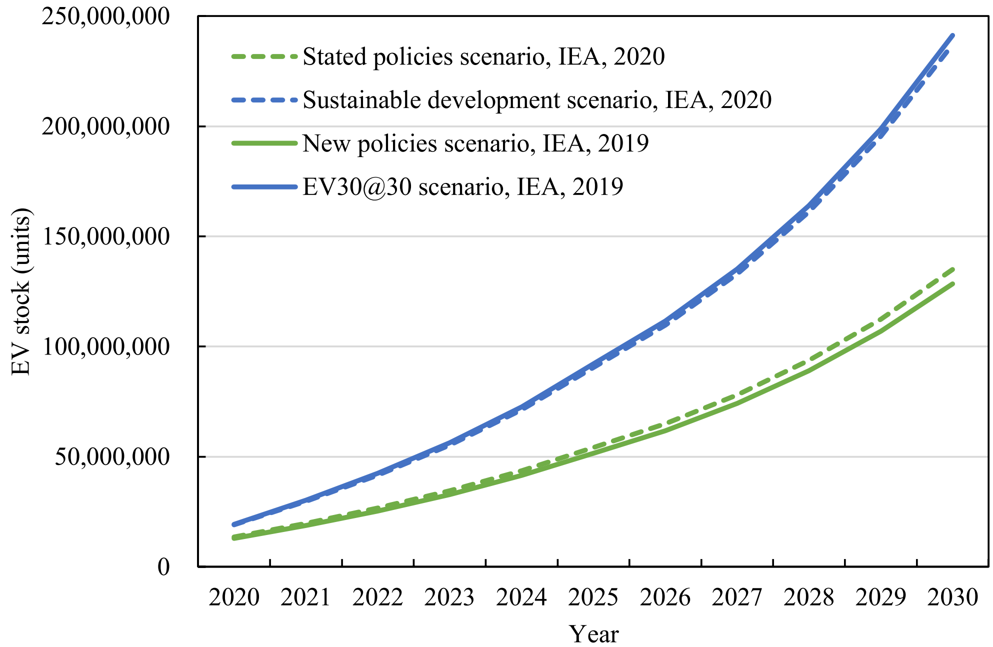
Supplementary Figure 18: Result of sensitivity analysis of 100% LFP market share (by 2030) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



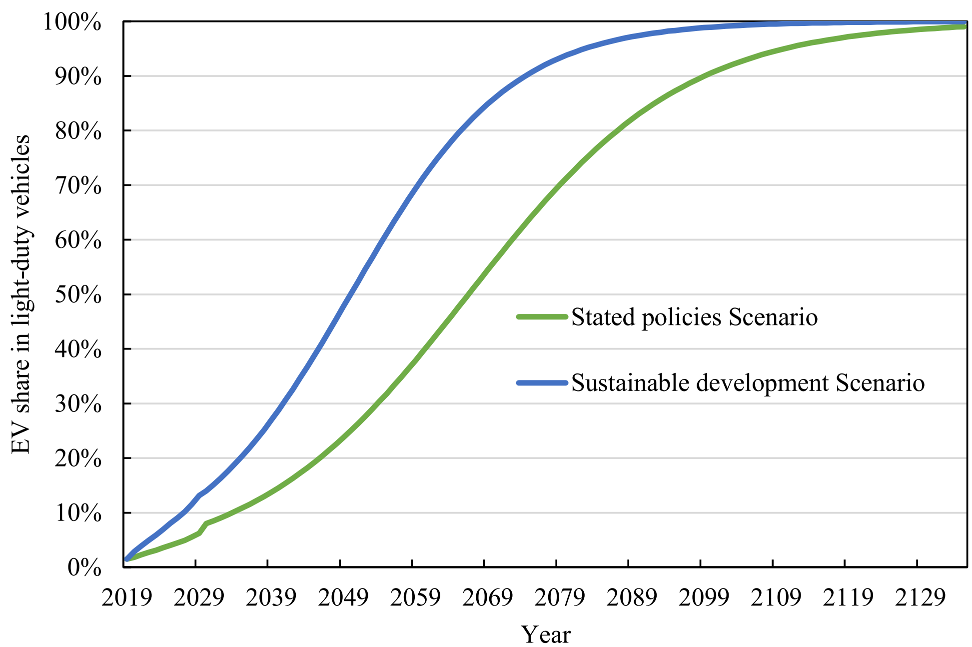
Supplementary Figure 19: Result of sensitivity analysis of 100% Li-S and Li-Air market share (by 2040) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



Supplementary Figure 20: Result of sensitivity analysis of lower battery lifespan (i.e. one EV will use 1.5 battery packs on average after 2020, while in the baseline scenario one EV will use 1 battery pack after 2020) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.

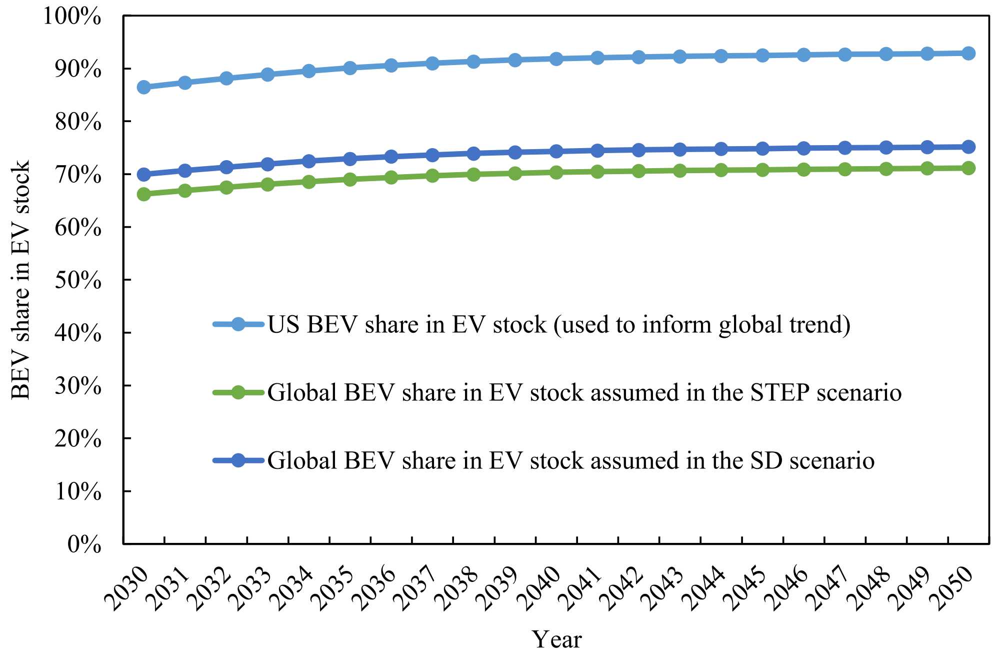


Supplementary Figure 21: EV stock estimations of stated policies scenario and sustainable development scenario from 2020-2030 of IEA global EV outlook 2020[1], in proportion with new policies scenario and EV30@30 scenario of IEA global EV outlook 2019[11], respectively.

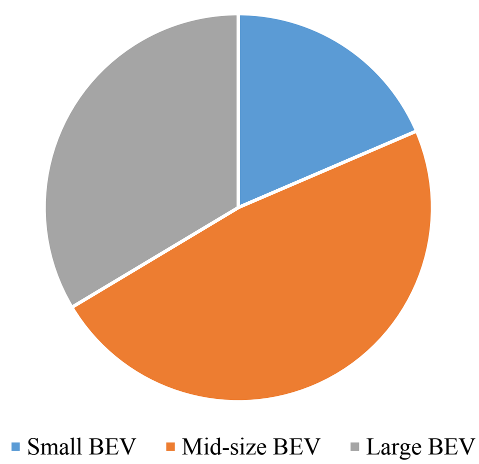


Supplementary Figure 22: Estimation of EV fleet penetration in stated policies scenario and sustainable development scenario of IEA (reach 100% until 2135). The EV fleet penetration until 2030 is based on the stated policies scenario and the sustainable development scenario of IEA[1], and we model the EV fleet penetration after 2030 by logistic model[12]. Here the figure shows the process of full transition to EVs in light-duty passenger vehicle market, and the time point when EV fleet share reach 100% in the stated policies scenario and the sustainable development scenario, if our estimations of 25%-50% of EV

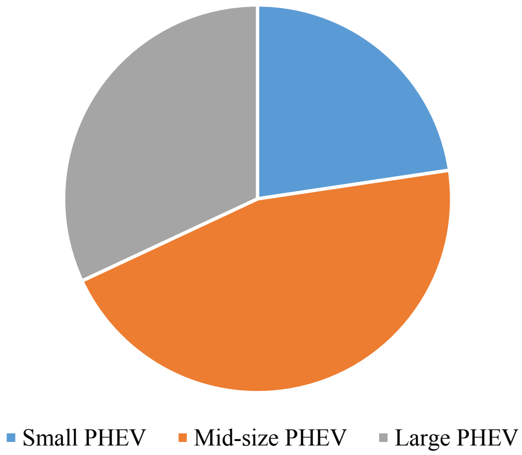
fleet share in 2050 are realized.



Supplementary Figure 23: Global BEV share in total EV stock in 2030-2050, in proportion with US BEV stock share projection by US Energy Information Administration[14].



Supplementary Figure 24: BEV sales market shares among small/mid-size/large segments. The market shares are based on cumulative sales until 2019 of each BEV model included in each BEV market segment. BEV sales market shares are assumed stable in 2020-2050, while sensitivity analysis is conducted.



Supplementary Figure 25: PHEV sales market shares among small/mid-size/large segments. The market shares are based on cumulative sales until 2019 of each PHEV model included in each PHEV market segment. PHEV sales market shares are assumed stable in 2020-2050, while sensitivity analysis is conducted.

Supplementary Tables

Supplementary Table 1: Sales-weighted average BEV range, fuel economy, and motor power. We collect sales of each BEV model include in small/mid-size/large car segments until 2019[15], and calculate the distribution of cumulative sales until 2019 of three car segments (to represent BEV market shares among small/mid-size/large car segments). The range, fuel economy, and motor power of each BEV segment are calculated by cumulative sales-weighted average method. The required battery capacity = EV range * fuel economy / 0.85, where 0.85 is the ratio of available battery capacity for driving EVs based on the assumption in the BatPaC model when calculating battery material compositions[3]. Average required battery capacity for BEVs reaches around 66 kWh.

BEVs	Range (miles)	Fuel economy (Wh/mile)	Electric motor power (kW)	Required capacity (kWh)
Small BEVs	96	291	101	33
Mid-size BEVs	194	291	169	66
Large BEVs	241	353	295	100

Supplementary Table 2: Sales-weighted average PHEV range, fuel economy, and motor power. Same data collection and calculation methods as the BEVs in the Supplementary Table 1. Average required battery capacity for PHEVs reaches around 12 kWh.

PHEVs	Range (miles)	Fuel economy (Wh/mile)	Electric motor power (kW)	Required capacity (kWh)
Small PHEVs	44	336	123	17
Mid-size PHEVs	22	303	55	8
Large PHEVs	22	470	61	12

Supplementary Table 3: The minimum, most likely, and maximum lifespans of EV batteries from 2005 to 2050 as input to the calculation of shape and scale parameters of Weibull lifespan distribution of batteries (unit: year, except for shape and scale parameters). Other chemistries refer to all battery chemistries except LFP. Note here battery lifespan assumptions are for illustration purposes which is linked to the assumptions of battery replacement rate and second-use rate.

Period	Chemistries	Minimum lifespan, a	Most likely lifespan, d	Maximum lifespan, c	Shape parameter, α	Scale parameter, β
2005-2019	All chemistries	1	8	15	3.1	7.9
2020-2050	Other chemistries	1	15	20	6.3	14.4
2020-2050	LFP	1	20	25	8.1	19.3

Supplementary Table 4: Specific energy of EV battery pack (unit: Wh/kg).

EV types	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
Small BEVs	122	169	151	153	164	176	183	192	295	365
Mid-size BEVs	129	178	160	163	174	186	193	202	308	383
Large BEVs	128	176	159	162	172	185	191	201	308	384
Small PHEVs	101	151	132	134	147	155	161	169	265	327
Mid-size PHEVs	74	109	103	104	109	116	118	121	224	272
Large PHEVs	75	115	106	108	114	119	121	124	234	287

Supplementary Table 5: Cumulative demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling, compared to global known reserves in 2019 (unit: Mt). Note Li demand includes Li ion demand (in the form of chemicals like Li_2CO_3) and Li metal demand in the Li-S/Air battery scenario, for example, 9.1 (4.8) for Li demand under the STEP and Li-S/Air scenario is shown in the form of total Li demand (Li metal demand). [*] Yearend production capacity for Al reserve. [‡] Si reserves are not available, but ample for use. Known reserves in 2019 are referred from USGS[16].

Materials	STEP scenario, NCX	STEP scenario, LFP	STEP scenario, Li-S/Air	SD scenario, NCX	SD scenario, LFP	SD scenario, Li-S/Air	Known reserves in 2019
Li	7.8	7.3	8.8 (4.6)	16.0	15.1	18.3 (9.6)	17
Co	8.1	3.5	4.3	16.8	7.1	8.8	7
Ni	43.0	18.1	21.9	88.9	37.2	44.7	89
Mn	5.2	2.2	2.7	10.6	4.5	5.5	810
Al	89.3	106.5	67.4	183.8	218.7	138.1	77.9[*]
Cu	59.8	66.8	37.6	121.0	134.6	75.4	870
Graphite	62.4	74.8	32.6	128.8	154.4	66.2	300
Si	2.4	1.0	1.2	5.0	2.1	2.4	Ample[‡]

Supplementary Table 6: Assumptions of second-use rate of batteries distinguished by LFP and other chemistries, based on the assumptions of EV and battery lifespan distribution (Supplementary Tables 10 and 11).

Periods	Battery chemistry	Second-use rate
2005-2019	LFP	100%
	Others	50%
2020-2050	LFP	100%
	Others	75%

Supplementary Table 7: Effects of recycling on cumulative demand for Li, Ni, Co, Mn, Al, Cu, graphite, and Si in 2020-2050. Numbers in the table represent reduction percentages by recycling compared to primary cumulative demand. Note Li demand includes Li ion demand (in the form of lithium chemicals) and Li metal demand in the Li-S/Air battery scenario. For example, 20.2% (8.0%) under the STEP scenario is shown in the form of reduction percentage of total Li demand (reduction percentage of Li metal demand). The reduction percentage of total Li demand is more than 2 times the reduction percentage of Li metal demand. From this table we can see the reduction of cumulative material demand through 2050 could reach around 20%-30% by recycling in the NCX and LFP scenarios, while it is raised to around 30%-40% in the Li-S/Air scenario due to the quick shift of battery chemistry in this scenario. There is no big difference of reduction percentages among materials and between the STEP scenario and SD scenario.

Materials	STEP scenario, NCX	STEP scenario, LFP	STEP scenario, Li-S/Air	SD scenario, NCX	SD scenario, LFP	SD scenario, Li-S/Air
Li	23.2%	23.1%	21.3% (8.4%)	21.6%	21.5%	19.9% (8.3%)
Co	28.2%	32.5%	44.0%	26.3%	29.5%	41.0%
Ni	23.6%	26.6%	37.7%	22.2%	24.6%	35.4%
Mn	28.1%	33.0%	44.1%	25.9%	29.4%	40.6%
Al	23.2%	22.6%	28.0%	21.7%	21.2%	26.0%
Cu	23.1%	22.8%	31.7%	21.6%	21.3%	29.6%
Graphite	24.2%	23.0%	38.2%	22.5%	21.5%	35.6%
Si	16.7%	18.0%	27.3%	15.9%	17.0%	25.9%

Supplementary Table 8: Closed-loop recycling potential (CLRP) in 2020-2029, 2030-2039, 2040-2050 in the STEP scenario by battery chemistry scenarios, recycling technologies, and second life use. There is no big difference of CLRP among three recycling technologies, however, the quality of recovered materials is key to realize the CLRP in practice.

Battery scenarios		*NCX*			*LFP*			*Li-S/Air*		
Time periods		*2020-2029*	*2030-2039*	*2040-2050*	*2020-2029*	*2030-2039*	*2040-2050*	*2020-2029*	*2030-2039*	*2040-2050*
Li ion	*No second life, pyro*	0.03	0.17	0.28	0.03	0.17	0.28	0.03	0.24	0.50
	No second life, hydro	0.03	0.17	0.28	0.03	0.17	0.28	0.03	0.24	0.50
	No second life, direct	0.03	0.17	0.28	0.03	0.17	0.28	0.03	0.24	0.50
	Second life, pyro	0.01	0.04	0.13	0.01	0.04	0.10	0.01	0.06	0.26
	Second life, hydro	0.01	0.04	0.13	0.01	0.04	0.10	0.01	0.06	0.26
	Second life, direct	0.01	0.04	0.13	0.01	0.04	0.10	0.01	0.06	0.26
Li metal	*No second life, mechanical*							0.00	0.00	0.11
	Second life, mechanical							0.00	0.00	0.03
Co	*No second life, pyro*	0.04	0.19	0.36	0.06	0.33	0.38	0.04	0.28	0.71
	No second life, hydro	0.04	0.19	0.36	0.06	0.33	0.38	0.04	0.28	0.71
	No second life, direct	0.03	0.17	0.33	0.06	0.30	0.35	0.03	0.25	0.65
	Second life, pyro	0.01	0.06	0.17	0.02	0.10	0.22	0.01	0.08	0.36
	Second life, hydro	0.01	0.06	0.17	0.02	0.10	0.22	0.01	0.08	0.36
	Second life, direct	0.01	0.05	0.15	0.02	0.10	0.20	0.01	0.08	0.33
Ni	*No second life, pyro*	0.02	0.15	0.29	0.04	0.26	0.30	0.02	0.23	0.56
	No second life, hydro	0.02	0.15	0.29	0.04	0.26	0.30	0.02	0.23	0.56
	No second life, direct	0.02	0.14	0.27	0.04	0.24	0.28	0.02	0.21	0.52
	Second life, pyro	0.01	0.04	0.12	0.01	0.08	0.16	0.01	0.06	0.27
	Second life, hydro	0.01	0.04	0.12	0.01	0.08	0.16	0.01	0.06	0.27
	Second life, direct	0.01	0.04	0.11	0.01	0.07	0.15	0.01	0.06	0.25
Mn	*No second life, pyro*	0.05	0.18	0.32	0.09	0.33	0.33	0.05	0.27	0.62
	No second life, hydro	0.06	0.20	0.35	0.10	0.36	0.36	0.06	0.30	0.68
	No second life, direct	0.05	0.18	0.32	0.09	0.33	0.33	0.05	0.27	0.62
	Second life, pyro	0.01	0.07	0.18	0.02	0.13	0.24	0.01	0.10	0.39
	Second life, hydro	0.02	0.07	0.19	0.03	0.14	0.26	0.02	0.11	0.43
	Second life, direct	0.01	0.07	0.18	0.02	0.13	0.24	0.01	0.10	0.39
Al	*No second life, pyro*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	No second life, hydro	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.21	0.36
	No second life, direct	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.21	0.36
	Second life, pyro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Second life, hydro	0.02	0.11	0.21	0.02	0.09	0.18	0.02	0.13	0.27
	Second life, direct	0.02	0.11	0.21	0.02	0.09	0.18	0.02	0.13	0.27
Cu	**No second life, pyro**	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.23	0.43
	No second life, hydro	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.23	0.43
	No second life, direct	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.23	0.43
	Second life, pyro	0.01	0.06	0.15	0.01	0.04	0.11	0.01	0.08	0.24
	Second life, hydro	0.01	0.06	0.15	0.01	0.04	0.11	0.01	0.08	0.24
	Second life, direct	0.01	0.06	0.15	0.01	0.04	0.11	0.01	0.08	0.24
Graphite	**No second life, pyro**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	No second life, hydro	0.03	0.18	0.29	0.03	0.16	0.28	0.03	0.27	0.57
	No second life, direct	0.03	0.18	0.29	0.03	0.16	0.28	0.03	0.27	0.57
	Second life, pyro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Second life, hydro	0.01	0.05	0.14	0.01	0.03	0.09	0.01	0.07	0.31
	Second life, direct	0.01	0.05	0.14	0.01	0.03	0.09	0.01	0.07	0.31
Si	**No second life, pyro**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	No second life, hydro	0.01	0.08	0.20	0.01	0.13	0.21	0.01	0.13	0.38
	No second life, direct	0.01	0.08	0.20	0.01	0.13	0.21	0.01	0.13	0.38
	Second life, pyro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Second life, hydro	0.00	0.02	0.07	0.00	0.03	0.09	0.00	0.03	0.16
	Second life, direct	0.00	0.02	0.07	0.00	0.03	0.09	0.00	0.03	0.16

Supplementary Table 9: Annual material demand in 2050 by three battery chemistry scenarios without recycling, with recycling, and with recycling and second life, and 2019 global mining production (unit: Mt) in the STEP scenario. The annual demand in 2050 for Li, Ni, Co, and graphite (natural graphite) from EV batteries alone exceed global mining production in 2019.

Materials	*Demand sceanrios*	*Battery scenarios / Mt*			*2019 annual production / Mt*	*Demand as percent of 2019 production*		
		NCX	*LFP*	*Li-S/Air*		*NCX*	*LFP*	*Li-S/Air*
Li	*Without recycling*	0.65	0.62	0.77	0.077	848%	807%	1002%
	With recycling	0.45	0.43	0.55		590%	565%	715%
	With recycling and second life	0.55	0.54	0.66		717%	707%	863%
Co	*Without recycling*	0.62	0.25	0.25	0.14	440%	179%	176%
	With recycling	0.37	0.15	0.10		265%	107%	72%
	With recycling and second life	0.49	0.19	0.14		347%	136%	102%
Ni	*Without recycling*	3.75	1.53	1.50	2.7	139%	57%	56%
	With recycling	2.57	1.04	0.81		95%	39%	30%
	With recycling and second life	3.16	1.25	1.04		117%	46%	38%
Mn	*Without recycling*	0.40	0.16	0.16	19	2%	1%	1%
	With recycling	0.25	0.10	0.07		1%	1%	0%
	With recycling and second life	0.30	0.12	0.08		2%	1%	0%
Al	*Without recycling*	7.53	9.08	5.25	64	12%	14%	8%
	With recycling	5.25	6.37	3.45		8%	10%	5%
	With recycling and second life	5.79	7.18	3.81		9%	11%	6%
Cu	*Without recycling*	5.06	5.68	2.73	20	25%	28%	14%
	With recycling	3.55	3.99	1.70		18%	20%	8%
	With recycling and second life	4.21	4.91	2.04		21%	25%	10%
Graphite	*Without recycling*	5.11	6.31	2.04	1.1	464%	574%	186%
	With recycling	3.48	4.40	1.08		317%	400%	98%
	With recycling and second life	4.27	5.57	1.37		388%	506%	125%
Si	*Without recycling*	0.25	0.10	0.10	7	4%	1%	1%
	With recycling	0.19	0.08	0.07		3%	1%	1%
	With recycling and second life	0.22	0.09	0.08		3%	1%	1%

Supplementary Table 10: Annual material demand in 2050 by three battery chemistry scenarios without recycling, with recycling, and with recycling and second life, and 2019 global mining production (unit: Mt) in the SD scenario.

Materials	*Demand sceanrios*	*Battery scenarios / Mt*			*2019 annual production / Mt*	*Demand as percent of 2019 production*		
		NCX	*LFP*	*Li-S/Air*		*NCX*	*LFP*	*Li-S/Air*
Li	*Without recycling*	1.33	1.26	1.57	0.077	1724%	1641%	2038%
	With recycling	0.91	0.87	1.11		1183%	1133%	1435%
	With recycling and second life	1.23	1.19	1.46		1593%	1542%	1899%
Co	*Without recycling*	1.25	0.51	0.50	0.14	894%	364%	358%
	With recycling	0.74	0.30	0.20		527%	214%	141%
	With recycling and second life	1.12	0.45	0.40		801%	320%	283%
Ni	*Without recycling*	7.63	3.10	3.05	2.7	282%	115%	113%
	With recycling	5.15	2.09	1.60		191%	77%	59%
	With recycling and second life	7.04	2.83	2.59		261%	105%	96%
Mn	*Without recycling*	0.81	0.33	0.33	19	4%	2%	2%
	With recycling	0.49	0.20	0.14		3%	1%	1%
	With recycling and second life	0.72	0.29	0.25		4%	2%	1%
Al	*Without recycling*	15.27	18.37	10.66	64	24%	29%	17%
	With recycling	10.51	12.71	6.91		16%	20%	11%
	With recycling and second life	13.54	16.47	9.22		21%	26%	14%
Cu	*Without recycling*	10.09	11.28	5.44	20	50%	56%	27%
	With recycling	6.97	7.80	3.32		35%	39%	17%
	With recycling and second life	9.24	10.50	4.75		46%	53%	24%
Graphite	*Without recycling*	10.39	12.84	4.16	1.1	944%	1167%	378%
	With recycling	6.98	8.82	2.15		634%	802%	196%
	With recycling and second life	9.55	12.09	3.48		868%	1099%	317%
Si	*Without recycling*	0.50	0.20	0.20	7	7%	3%	3%
	With recycling	0.38	0.16	0.13		5%	2%	2%
	With recycling and second life	0.47	0.19	0.18		7%	3%	3%

Supplementary Table 11: Modelled material compositions of a Li-S (600 Wh/kg) and a Li-Air (1000 Wh/kg) pack used for sensitivity analysis. (unit: kg per battery pack)

EV types	Materials	Li-Sulphur	Li-Air
Small BEVs	Li ion	0.19	0.12
	Li metal	3.62	1.69
	Al	16.42	9.92
	Cu	6.44	0.27
	Al in modules	6.86	4.18
	Cu in modules	6.14	0.10
Mid-size BEVs	Li ion	0.39	0.24
	Li metal	7.30	3.40
	Al	30.20	18.25
	Cu	13.33	0.77
	Al in modules	13.72	8.36
	Cu in modules	12.53	0.29
Large BEVs	Li ion	0.59	0.36
	Li metal	11.03	5.13
	Al	45.64	27.58
	Cu	21.75	2.12
	Al in modules	20.63	12.58
	Cu in modules	20.52	1.39
Small PHEVs	Li ion	0.10	0.06
	Li metal	1.91	0.89
	Al	7.26	4.39
	Cu	7.52	2.62
	Al in modules	3.53	2.15
	Cu in modules	4.37	2.62
Mid-size PHEVs	Li ion	0.05	0.03
	Li metal	0.88	0.41
	Al	3.97	2.40
	Cu	4.51	1.84
	Al in modules	1.70	1.04
	Cu in modules	3.06	1.84
Large PHEVs	Li ion	0.07	0.04
	Li metal	1.32	0.61
	Al	5.48	3.31
	Cu	7.26	3.05
	Al in modules	2.49	1.52
	Cu in modules	5.08	3.05

Supplementary Table 12: Sensitivity analysis of lower battery lifespan (i.e. one EV will use 1.5 battery packs on average after 2020, while in the baseline scenario one EV will use 1 battery pack after 2020) for cumulative demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling, compared to global known reserves in 2019 (unit: Mt). * Yearend production capacity for Al reserve. ‡ Si reserves are not available, but ample for use. Known reserves in 2019 are referred from USGS[16].

Materials	STEP scenario, NCX scenario	STEP scenario, NCX scenario, with lower battery lifespan	SD scenario, NCX scenario	SD scenario, NCX scenario, with lower battery lifespan	Known reserves in 2019
Li	7.8	8.8	16.0	18.1	17
Co	8.1	9.2	16.8	18.9	7
Ni	43.0	49.0	88.9	100.6	89
Mn	5.2	5.8	10.6	12.0	810
Al	89.3	101.6	183.8	207.6	77.9*
Cu	59.8	68.1	121.0	136.9	870
Graphite	62.4	70.9	128.8	145.3	300
Si	2.4	2.8	5.0	5.7	Ample‡

Supplementary Table 13: Compiled EPA car size class[17] used in this study. Note here small cars include two-Seaters, minicompact sedans, subcompact sedans, and compact sedans by the EPA car size class. Large cars include large sedans, small station wagons, SUVs, and vans by the EPA car size class.

Class	Passenger & Cargo Volume (Cu. Ft.)
Small	< 110
Mid-size	110 to 119
Large	> 119

Supplementary Table 14: Summary of capacity of the cathode and anode of battery chemistry as input to the BatPaC model. The majority of cathode and anode capacity are kept as defaults in the BatPaC model[3], unless otherwise based on Supplementary Tables 18, 19, and 20 or references. We use composite graphite anode with 9 wt% Si to represent Graphite (Si) anode in this table, and its capacity is from[18].

Battery chemistry	Cathode	Cathode capacity (mAh/g)	Anode	Anode capacity (mAh/g)
LFP	$LiFePO_4$	150	Graphite	360
NCA	$LiNi_{0.8}0Co_{0.15}Al_{0.05}O_2$	200	Graphite	360
NCM111	$Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$	155	Graphite	360
NCM523	$Li_{1.05}(Ni_{0.5}Mn_{0.3}Co_{0.2})_{0.95}O_2$	158	Graphite	360
NCM622	$Li_{1.05}(Ni_{0.6}Mn_{0.2}Co_{0.2})_{0.95}O_2$	180	Graphite	360
NCM622-Graphite (Si)	$Li_{1.05}(Ni_{0.6}Mn_{0.2}Co_{0.2})_{0.95}O_2$	180	Graphite (Si)	517[18]
NCM811-Graphite (Si)	$Li_{1.05}(Ni_{0.8}Mn_{0.1}Co_{0.1})_{0.95}O_2$	191	Graphite (Si)	517[18]
NCM955-Graphite (Si)	$Li_{1.05}(Ni_{0.9}Mn_{0.05}Co_{0.05})_{0.95}O_2$	211	Graphite (Si)	517[18]

Supplementary Table 15: The minimum, most likely, and maximum lifespans of EVs from 2005 to 2050 as input to the calculation of shape and scale parameters of Weibull lifespan distribution of EVs (unit: year, expect for shape and scale parameters). Also see Supplementary Figure 21 below.

Period	Minimum lifespan, a	Most likely lifespan, d	Maximum lifespan, c	Shape parameter, α	Scale parameter, β
2005-2050	1	15	20	6.3	14.4

Supplementary Table 16: Assumptions of battery replacement rate, based on the assumptions of EV and battery lifespan distribution (Supplementary Tables 10 and 11).

Period	Battery replacement rate
2005-2019	50%
2020-2050	0%

Supplementary Table 17: Review of cathode capacity of NCM523 (unit: mAh/g). We use the average number in this table as input into the BatPaC model to calculate battery material compositions of NCM523 chemistry.

References	Cathode capacity of NCM523
Ref1[19]	157
Ref2[20]	164
Ref3[21]	150
Ref3[21]	142
Ref3[21]	175
Average	158

Supplementary Table 18: Review of cathode capacity of NCM811 (unit: mAh/g). We use the average number in this table as input into the BatPaC model to calculate battery material compositions of NCM811-Graphite (Si).

References	Cathode capacity of NCM811
Ref1[22]	207
Ref2[19]	200
Ref3[21]	194
Ref3[21]	185
Ref3[21]	178
Ref3[21]	186
Ref3[21]	188
Ref3[21]	193
Ref4[23]	192
Average	191

Supplementary Table 19: Review of cathode capacity of NCM955 (unit: mAh/g). We use the average number in this table as input into the BatPaC model to calculate battery material compositions of NCM955-Graphite (Si).

References	Cathode capacity of NCM955
Ref1[21]	205
Ref2[23]	217
Average	211

Supplementary Table 20: Reference chemistry and changing parameters as input to the BatPaC model for the calculation of the material compositions of the non-existing battery chemistries in the BatPaC model. Here we assume a linear growth for open circuit voltage (OCV) at different levels of battery state of charge (SOC) from NCM523, to NCM622-Graphite (Si), to NCM811- Graphite (Si), to NCM955- Graphite (Si). The OCV of NCM523 = the average of OCV(NCM111) and OCV(NCM622) in the BatPaC model. The OCV of NCM622-Graphite (Si) = OCV(NCM622) – 0.076 (see Supplementary Note 1 for the assuming average voltage difference between graphite (Si) anode and graphite anode). Similarly, the OCV of NCM811-Graphite (Si) = 2*OCV(NCM622) – OCV(NCM523) – 0.076. The OCV of NCM955-Graphite (Si) = 2*OCV(NCM811-Graphite (Si)) – OCV(NCM622-Graphite (Si)). Cathode capacity is from Supplementary Table 21. The Li, Ni, Co, and Mn contents in the cathode active material are calculated by the stoichiometry of battery cathode shown in the Supplementary Table 21.

Battery chemistry	NCM523	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)
Reference chemistry	NCM111	NCM622	NCM622	NCM622
Cathode capacity (mAh/g)	158	180	191	211
Anode capacity (mAh/g)	360	517	517	517
OCV at 20% SOC (V)	3.5405	3.489	3.5135	3.538
OCV at 50% SOC (V)	3.7105	3.674	3.7135	3.753
OCV at 80% SOC (V)	3.95	3.924	3.974	4.024
OCV at 100% SOC (V)	4.15	4.124	4.174	4.224
Li (g/g active material)	0.07751513	0.077221916	0.076949595	0.076813626
Ni (g/g active material)	0.296520724	0.354478904	0.470971788	0.528915777
Co (g/g active material)	0.119093288	0.118642798	0.059112203	0.031060614
Mn (g/g active material)	0.166530137	0.11060014	0.055105055	0.027508722

Supplementary Table 21: Review of the specific energy of Li-S chemistry on cell level (unit: Wh/kg).

References	Battery shape	Specific energy	Technology readiness
Ref1[24]		400	
Ref2[25]		370	
Ref3[26]		300-620	R&D
Ref4[27]	Pouch	300-400	
Ref4[27]	Pouch	500-600	R&D
Ref5[28]		400-620	
Ref6[24]	Pouch	350-400	Commercial
Ref7[29]	Pouch	300	Lab

Supplementary Table 22: Review of the specific energy of Li-Air chemistry on cell level (unit: Wh/kg).

References	Battery shape	Specific energy	Technology readiness
Ref1[24]		1700	
Ref2[25]		1700	
Ref3[26]		500-900	
Ref4[30]	Pouch	362	R&D
Ref5[31]		520	
Ref6[32]	Coin	1000	
Ref7[33]	Folded structure	1214	
Ref8[28]		500-1000	

Supplementary Table 23: EV battery material compositions on pack level calculated by the BatPaC model (unit: kg per battery pack). Note the material compositions of Li-S and Li-Air are calculated based on literature and report data.

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
Small BEVs	Li ion	3.29	3.40	4.68	4.54	3.94	4.00	3.72	3.33	0.29	0.23
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.44	3.37
	Ni	0.00	21.97	11.50	16.73	17.38	17.74	21.97	22.10	0.00	0.00
	Co	0.00	4.14	11.55	6.72	5.82	5.94	2.76	1.30	0.00	0.00
	Mn	0.00	0.00	10.77	9.40	5.42	5.53	2.57	1.15	0.00	0.00
	Al	58.66	45.71	49.02	48.42	46.33	44.33	43.23	42.23	24.63	19.83
	Cu	29.14	24.51	26.74	26.29	24.71	24.97	24.16	23.88	9.66	0.55
	Graphite	39.18	35.30	36.19	35.74	34.95	23.58	23.17	22.67	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	2.33	2.29	2.24	0.00	0.00
Mid-size BEVs	Li	6.62	6.84	9.43	9.14	7.94	8.06	7.49	6.72	0.58	0.47
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.95	6.79
	Ni	0.00	44.26	23.18	33.71	35.00	35.73	44.26	44.51	0.00	0.00
	Co	0.00	8.33	23.27	13.54	11.71	11.96	5.55	2.61	0.00	0.00
	Mn	0.00	0.00	21.70	18.93	10.92	11.15	5.18	2.32	0.00	0.00
	Al	106.87	83.41	87.69	86.68	84.12	80.35	78.98	77.11	45.30	36.50
	Cu	56.33	49.16	49.70	49.17	48.54	49.08	48.58	48.03	20.00	1.53
	Graphite	78.84	70.93	72.79	71.87	70.24	47.39	46.55	45.55	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	4.69	4.60	4.51	0.00	0.00
Large BEVs	Li	10.01	10.34	14.24	13.81	11.99	12.17	11.32	10.15	0.88	0.71

	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.54	10.27
	Ni	0.00	66.86	35.02	50.93	52.88	53.97	66.86	67.25	0.00	0.00
	Co	0.00	12.59	35.16	20.46	17.70	18.06	8.39	3.95	0.00	0.00
	Mn	0.00	0.00	32.78	28.60	16.50	16.84	7.82	3.50	0.00	0.00
	Al	162.87	127.52	134.00	132.45	128.57	122.92	120.86	118.01	68.46	55.16
	Cu	92.60	80.24	81.37	80.50	79.37	79.90	79.05	78.09	32.63	4.25
	Graphite	119.32	107.42	110.22	108.83	106.37	71.77	70.51	69.00	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	7.10	6.97	6.82	0.00	0.00
Small PHEVs	Li	1.74	1.79	2.47	2.39	2.08	2.11	1.96	1.76	0.15	0.12
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.86	1.78
	Ni	0.00	11.56	6.05	8.80	9.14	9.33	11.56	11.63	0.00	0.00
	Co	0.00	2.18	6.08	3.53	3.06	3.12	1.45	0.68	0.00	0.00
	Mn	0.00	0.00	5.66	4.94	2.85	2.91	1.35	0.60	0.00	0.00
	Al	35.16	21.27	26.66	26.32	21.82	20.95	20.38	19.59	10.89	8.78
	Cu	34.72	24.49	25.98	25.65	24.76	25.30	24.74	24.02	11.27	5.24
	Graphite	20.47	18.48	18.95	18.72	18.30	12.34	12.13	11.87	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	1.22	1.20	1.17	0.00	0.00
Mid-size PHEVs	Li	0.81	0.83	1.13	1.10	0.96	0.97	0.90	0.81	0.07	0.06
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	0.82
	Ni	0.00	5.30	2.77	4.04	4.19	4.28	5.30	5.33	0.00	0.00
	Co	0.00	1.00	2.79	1.62	1.40	1.43	0.66	0.31	0.00	0.00
	Mn	0.00	0.00	2.60	2.27	1.31	1.33	0.62	0.28	0.00	0.00
	Al	23.16	15.10	15.59	15.40	15.01	12.41	12.30	12.23	5.95	4.79

	Cu	29.89	20.06	20.05	19.82	19.63	20.37	20.32	20.35	6.76	3.67
	Graphite	9.43	8.55	8.77	8.66	8.46	5.71	5.61	5.49	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	0.56	0.55	0.54	0.00	0.00
Large PHEVs	Li	1.21	1.24	1.71	1.66	1.44	1.46	1.36	1.22	0.11	0.09
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.98	1.23
	Ni	0.00	7.99	4.18	6.09	6.32	6.45	7.99	8.04	0.00	0.00
	Co	0.00	1.50	4.20	2.44	2.11	2.16	1.00	0.47	0.00	0.00
	Mn	0.00	0.00	3.92	3.42	1.97	2.01	0.93	0.42	0.00	0.00
	Al	35.69	20.27	21.45	21.17	20.16	19.75	19.56	19.41	8.23	6.63
	Cu	44.74	30.21	30.86	30.52	29.50	30.42	30.39	30.45	10.90	6.10
	Graphite	14.18	12.84	13.17	13.01	12.72	8.58	8.42	8.24	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	0.85	0.83	0.82	0.00	0.00

Supplementary Table 24: Comparisons of three EV battery recycling technologies by recycled material type, recycling efficiency, and the quality of recovered materials, where mechanical recycling is especially for the recovery of Li metal (a different form compared to Li ion in chemicals), Al, and Cu form Li-S and Li-Air chemistry. Numbers in the table show the material recycling efficiencies. The different colors show the feasibility of recovered materials reused in new batteries production (i.e. closed-loop recycling). Yellow color indicates the economic feasibility of closed-loop recycling is in question, but maybe become potentially economical with future technology development and price fluctuance of recovered materials. Pyro and hydro recycling are already commercially available, while direct recycling and mechanical recycling marked with star (*) are in still lab-scale development.

Technology	Li	Ni	Co	Mn	Al	Cu	Graphite	Si
Pyro	90%	98%	98%	90%	0%	90%	0%	0%
Hydro	90%	98%	98%	98%	90%	90%	90%	90%
Direct*	90%	90%	90%	90%	90%	90%	90%	90%
Mechanical*	90%				90%	90%		

	Not present
	Lost
	Potentially economical
	Eonomical

Supplementary Table 25: Material compositions of a BEV battery with 110 kWh capacity used for sensitivity analysis. (unit: kg per battery pack)

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
BEV with 110 kWh capacity	Li ion	10.98	11.35	15.63	15.16	13.16	13.36	12.42	11.13	0.96	0.78
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.15	11.26
	Ni	0.00	73.36	38.42	55.88	58.02	59.22	73.36	73.79	0.00	0.00
	Co	0.00	13.81	38.58	22.45	19.42	19.82	9.21	4.33	0.00	0.00
	Mn	0.00	0.00	35.97	31.39	18.10	18.48	8.58	3.84	0.00	0.00
	Al	172.79	135.08	141.95	140.31	136.19	130.17	127.98	124.94	75.12	60.53
	Cu	99.58	86.46	87.62	86.66	85.42	86.01	85.07	84.02	35.80	4.66
	Graphite	130.80	117.71	120.79	119.27	116.56	78.64	77.26	75.60	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	7.78	7.64	7.48	0.00	0.00
	Al in modules	85.70	66.31	69.31	68.54	66.54	64.01	62.84	61.37	33.96	27.60
	Cu in modules	95.86	83.15	84.30	83.38	82.18	82.70	81.80	80.78	33.78	3.04

Supplementary Table 26: Material compositions of a PHEV battery with 10 kWh capacity used for sensitivity analysis. (unit: kg per battery pack)

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
PHEV with 10 kWh capacity	Li ion	1.01	1.04	1.42	1.38	1.20	1.22	1.13	1.02	0.09	0.07
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.65	1.02
	Ni	0.00	6.66	3.49	5.07	5.27	5.37	6.66	6.70	0.00	0.00
	Co	0.00	1.25	3.50	2.04	1.76	1.80	0.84	0.39	0.00	0.00
	Mn	0.00	0.00	3.26	2.85	1.64	1.68	0.78	0.35	0.00	0.00
	Al	29.81	16.90	17.27	17.13	16.86	16.45	16.29	16.14	6.28	5.07
	Cu	34.74	23.03	22.70	22.67	22.74	23.23	23.22	23.30	6.50	3.02
	Graphite	11.83	10.71	10.99	10.86	10.61	7.16	7.03	6.88	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	0.71	0.70	0.68	0.00	0.00
	Al in modules	15.69	8.75	8.83	8.72	8.63	8.57	8.49	8.46	3.05	2.48
	Cu in modules	22.07	11.57	11.19	11.08	11.20	11.65	11.65	11.80	3.78	3.02

Supplementary Methods

Supplementary Method 1

The probability of Weibull lifespan distribution[34] is given by equation (1):

$$f(y) = \begin{cases} \alpha\beta^{-\alpha}(y-a)^{\alpha-1}exp\left\{-\left(\frac{y-a}{\beta}\right)^{\alpha}\right\} & if\ y > a; \\ 0 & otherwise. \end{cases} \tag{1}$$

where α is the shape parameter (α > 0); β is the scale parameter (β > 0); y is the year; a is the minimum lifespan.

By assuming the cumulative probability of Weibull lifespan distribution function between the minimum and the maximum lifespans as 99.7% (based on the normal distribution), the α and β in the Weibull lifespan distribution can be calculated by equations (2) and (3)[34]:

$$1 - exp\left\{-\left(\frac{c-a}{\beta}\right)^{\alpha}\right\} = 99.7\% \tag{2}$$

$$d = a + \beta\left(\frac{\alpha-1}{\alpha}\right)^{1/\alpha} \tag{3}$$

where c is the maximum lifespan; d is the most likely lifespan.

Supplementary Method 2

Based on above assumptions on lifespan distributions of EVs and replacement rate and reuse rate of EV batteries, we calculate the battery flows by equations (4) and (5):

$$B_{e,b,out}(y) = B_{e,b,in}(y) - \Delta B_{e,b,stk}(y) \tag{4}$$

$$B_{e,b,out}(y) = 1.5 * (B_{e,b,in}(2005) \times \int_{y-2005}^{y-2004} f_E(y)dy + B_{e,b,in}(2006) \times \int_{y-2006}^{y-2005} f_E(y)dy + \ \dots$$

$$+B_{e,b,in}(2019) \times \int_{y-2019}^{y-2018} f_E(y)dy) + B_{e,b,in}(2020) \times \int_{y-2020}^{y-2019} f_E(y)dy \dots + B_{e,b,in}(y-1) \times \int_{1}^{2} f_E(y)dy \tag{5}$$

where E, B, in, stk, and out are abbreviations of EV, battery, inflow, stock, and outflow respectively; e and b are the categories of EV and battery; $f_E(y)$ are lifespan distributions of EVs. 1.5 in the equation (5) refer to battery replacement means one single EV uses 1.5 battery packs on average during EV lifespan.

Supplementary Notes

Supplementary Note 1

Average battery cell voltage = Average voltage of cathode – average voltage of anode. Relative to Li^+/Li, the average voltage of graphite (360 mAh/g) and Si are 0.15 V and 0.4 V. The average voltage of the graphite (Si) anode with 517 mAh/g active capacity can be estimated as (360/517)*0.15 + (157/517)*0.4 = 0.226 (V), based on assumption of a capacity averaged linear combination of graphite and Si[35]. Therefore, compared to NCM622-Graphite, the open circuit voltage of NCM622-Graphite (Si) will be reduced by 0.226-0.15 = 0.076 (V)[35].

Supplementary Note 2

The cell material compositions of Li-S batteries are obtained from[29], where required cell materials are scaled linearly by a factor between cell level energy capacity and required capacity of BEVs/PHEVs (see Supplementary Tables 2 and 3). The pack components of Li-S is calculated based on the pack configurations of default NCA chemistry in the BatPaC model[3], that is to say the weight ratio of cell components and pack components, as well as the weight ratios of various components/materials in the pack configurations for Li-S are assumed equal to the NCA chemistry in the BatPaC model[3]. Similarly, we also use the same calculation methods for the material compositions of Li-Air packs, based on the cell level material compositions of the Li-Air battery from[30].

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