Supplementary Information

Critical mineral resource availability and lead times may constrain multi-decadal supplies amid growing demands

Brinda Yarlagadda[1], Anastasiia Zagoruichyk[1], Yang Qiu[1], Karan Bhuwalka[2], Pralit Patel[1], Neal Graham[1], Marshall Wise[1], Maggie Liu[1], Siddarth Durga[1], Allen Fawcett[1], and Gokul Iyer[1]

[1]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA

[2]Stanford University, Stanford, CA, USA

S1 Literature review

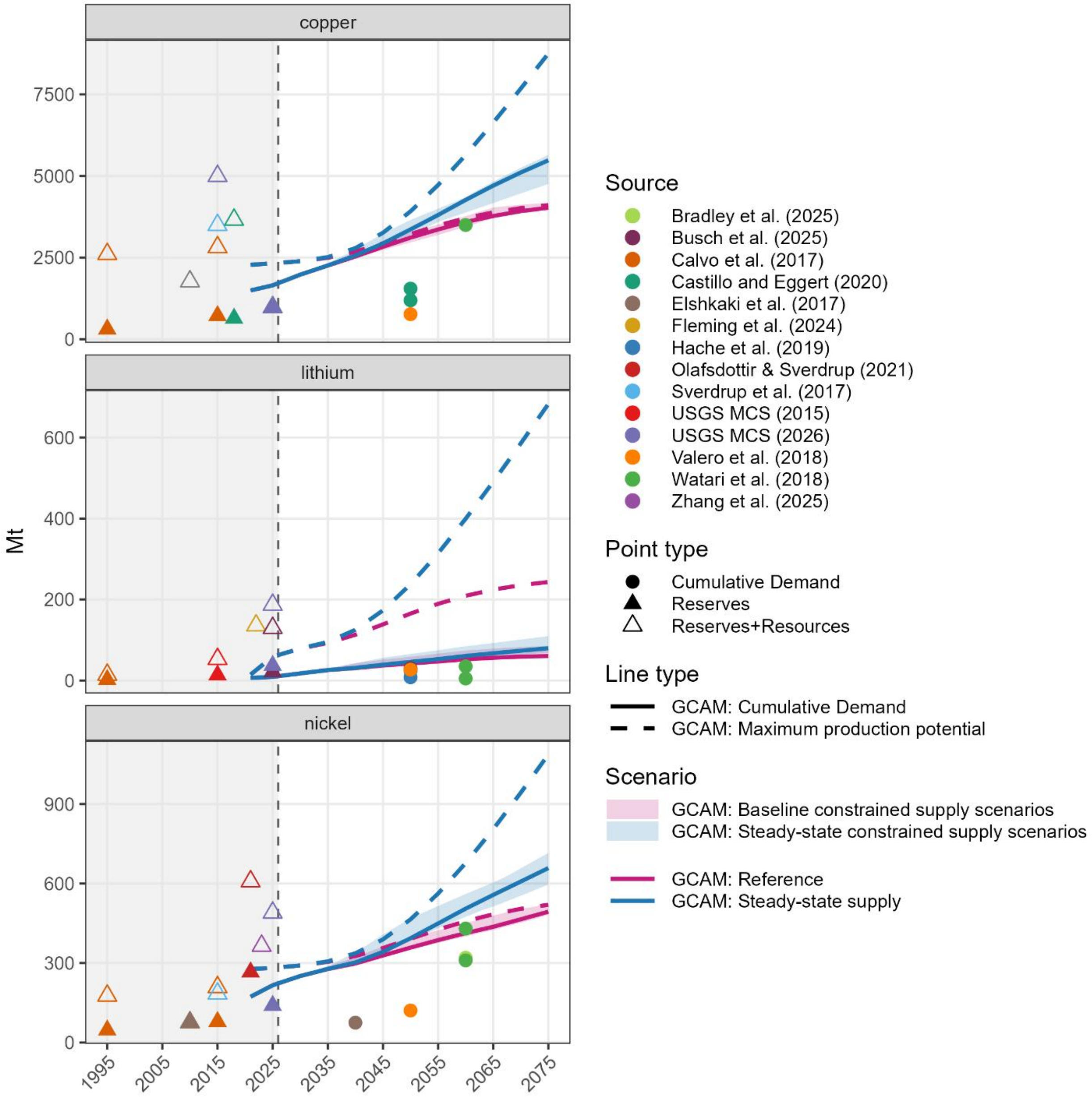

Figure S1. Comparison of reserves, reserves + resources, and cumulative demand (Mt) across literature (points) and GCAM projections (lines) over 1995-2075.

We note a few key observations from **Figure S1**. First, estimates of reserves (filled triangles) and reserves + resources (open triangles) have generally increased over time in the historical period. This lends credibility to the theory that supplies will not peak and run out in this century, but will continue to grow, as they have done in past decades. Second, several studies provide projections of future demand (circles) but not future projections of cumulative supply availability. Thus, through this study, we fill a core gap in the literature, providing time-evolving maximum production potential (dashed lines) which set the scale of total cumulative supply availability. This maximum production potential varies depending on our assumptions about new resource discovery (baseline constrained supply vs. steady-state constrained supply) and lead times (average vs. short lead times). By running GCAM, we then derive model-resolved cumulate demand (solid lines and ribbons) across each of the scenarios.

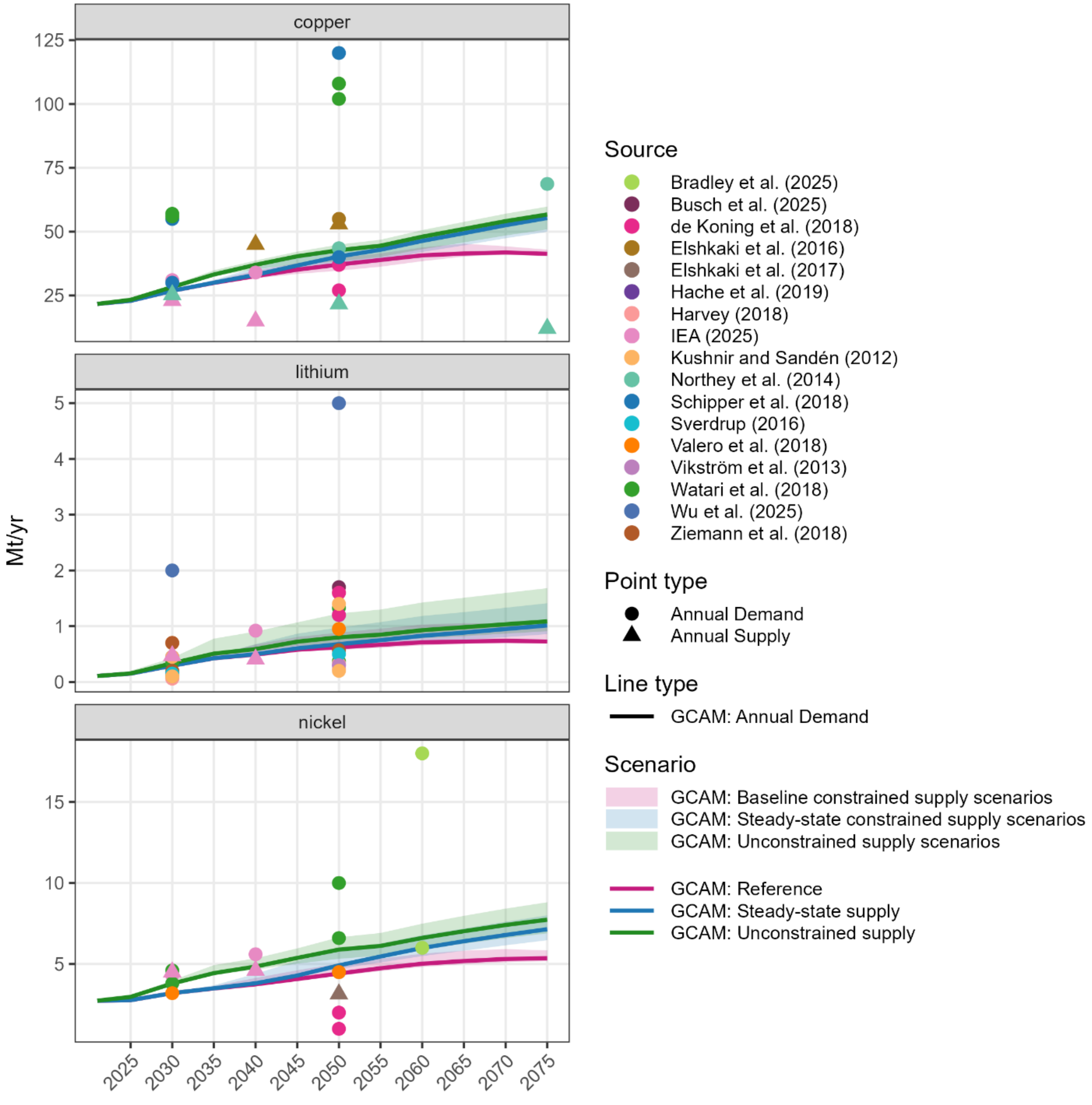

Figure S2. Comparison of annual supply and demand projections (Mt/yr) across literature and GCAM projections (annual demand only), 2021-2075.

We note a few key observations from **Figure S2**. Several studies provide future projections of annual demand (circles), while comparatively less provide projections of annual supply (triangles). However, many of these annual supply projections (e.g. from IEA[1]) only consider what can be produced from existing or announced mine projects, and don't include future potential supply from mine projects in earlier stages or from resources that are not yet associated with any projects. Thus, most annual supply projections show flat or declining trends over time, while annual demand projections are increasing over the same time period. In this study, we fill a core gap in the literature by accounting for future dynamic future supplies (i.e. supply projections that account for mining projects that are still in development, or new resource discoveries). Note, we only show GCAM annual demand projections in this figure, not annual supply projections— because our time-evolving supply inputs are in cumulative rather than annual terms, thus an annual supply projection is not available. GCAM's future supply projections (cumulative maximum production potential) are shown on **Figure S1** (cumulative comparison figure).

Table S1. Summary of mineral extraction costs ($/ton), historical global reserve and resource estimates (Mt) future cumulative demand (Mt), annual supply (Mt/yr) and annual demand (Mt/yr) projections.

	Study	**Notes**	**Extraction cost range ($/ton)**	**Historical estimates of global reserves (Mt)**	**Historical estimates of global resources (including reserves) (Mt)**	**Projections of cumulative demand (Mt)**	**Projections of annual mine supply (Mt/yr)**	**Projections of annual demand (Mt/yr)**
Copper	Castillo and Eggert (2020)[2]	Reserves and resources data are based on Mudd and Jowitt (2018)	1543-14,330	2018: 641	2018: 3,020			
	Calvo et al. (2017)[3]	USGS data is the primary source		1995: 310 2015: 720	1995: 2,300 2015: 2,100	2050: 1,193-1,551 2100: 4,788-7,136		
	USGS MCS (2026)[4]	The most recent USGS assessment of		2025: 980	2015: 5,000			

		global copper *resources* was conducted in 2015						
	IEA (2025)[1]						2030: 23 2040: 15	2030: 31 2040: 34
	Northey et al. (2014)[5]				2010: 1,771		2030: 25.3 2050: 21.7 2075: 12.1 2100: 0.10	2050: 43.5 2075: 68.7 2100: 99.1
	Elshkaki et al. (2016)[6]	Market First Scenario					2040: 45 2050: 53	2050: 55
	Sverdrup et al. (2017)[7]		4000-8,000,000		2015: 3,500			
	de Koning et al. (2018)[8]							2050: 27-37
	Schipper et al. (2018)[9]							2030: 30-55 2050: 40-120 2100: 60-450
	Watari et al. (2018)[10]							2030: 56-57 2050: 102-108
	Valero et al. (2018)[11]					2060: 3,500		
Lithium	Calvo et al. (2017)[3]	USGS data is the primary source		1995: 2.2	1995:12	2016-2050: 767		
	USGS MCS (2015)[4]			2015: 13.5	2015: 39.5			
	Fleming et al. (2024)[12]		3,900–10,500 ($/t LCE)		2022: 726 (LCE)			
	Busch et al. (2025)[13]	Reference Scenario; Demonstrated + Inferred Resources	7,491-14,177 ($/t LCE)	2025: 21.6	2025: 108			2050: 1.7
	USGS MCS (2026)[4]			2025: 37	2025: 150			
	IEA (2025)[1]					2022-2050: 30	2030: 0.47 2040: 0.41	2030: 0.45 2040: 0.92
	Wu et al. (2025)[14]		2800-8000 ($/t LCE)					2030: 2 2050: 5
	Wesselkaemper et al. (2026)[15]		3790-23,529 ($/t LCE)					
	Watari et al. (2018)[10]							2030: 0.12-0.35 2050: 0.37-1.33
	Hache et al. (2019)[16]							2030: 0.17-0.45 2050: 0.30-1.2
	Valero et al. (2018)[11]					2015-2060: 5-35		2030: 0.70 2050: 0.95
	Ziemann et al. (2018)[17]					2005-2050: 8-24		2030: 0.20-0.70 2050: 0.57-1.6
	de Koning [8]et al. (2018)					2016-2050: 27		2050: 1.2-1.6
	Harvey (2018)[18]							2030:0.06-0.07 2050: 0.23-0.33

	Sverdrup (2016)[19]							2030: 0.15 2050: 0.50
	Vikström et al. (2013)[20]							2030: 0.10 2050: 0.30
	Kushnir and Sandén (2012)[21]							2030: 0.10-0.45 2050: 0.20-1.4
Nickel	USGS MCS (2026)[4]			2025: 140	2025: 350			
	IEA (2025)[1]						2030: 4.5 2040: 4.6	2030: 4.3 2040: 5.6
	Calvo et al. (2017)	USGS data is the primary source		1995: 47 2015: 79	1995: 130 2015: 130			
	Elshkaki et al. (2017)[22]	Market World Scenario; USGS data is the primary source for estimating Reserves		2010: 76		2040: 75	2050: 3.15	2050: 4.5
	Sverdrup et al. (2017)				2015: 185			
	Olafsdottir & Sverdrup (2021)[23]	Deposit-by-deposit tally based on the available literature, adding up the metal contents		2021: 266	2021: 342			
	Zhang et al. (2025)[24]	USGS data is the primary source			2023: 365			
	R. Basuhi et al. (2024)[25]		8,000 – 21,000					
	Bradley et al. (2025)[26]	Business as Usual Scenario				2015-2060: 200-320		2060: 6-18
	Wesselkaemper et al. (2026)[15]		6785-21,710					
	Watari et al. (2018)[10]					2015-2060: 310-430		2030: 3.8-4.6 2050: 6.6-10
	Valero et al. (2018)[11]					2016-2050: 121		2030: 3.2 2050: 4.5
	de Koning et al. (2018)[8]							2050: 1-2

S2 Additional Results

S2.1 Definitions of terms and units used in figures

Annual production (Mt/yr): Model-derived *output* of production in a particular year.

Cumulative production (Mt): Model-derived *output* of cumulative production up to a particular year. In this study, we start cumulation from 2021, our model base year.

Maximum production potential (Mt): Model *input* of total economic reserves (Mt) associated with mines that are assumed to be available for production in a particular year.

> Note: The ratio of cumulative production to maximum production potential indicates whether the quantity of mineral supply is binding. If global cumulative production/production potential = 1, the quantity of mineral supply is fully binding.

The figure 2 legend classifies annual and cumulative production over time based on the proportion that comes from reserves in different stages (according to what stage these reserves are in as of 2021). By the year in which this production occurs, the associated reserves would, by definition, be associated with mines that are available for production.

Economic reserves associated with operating mines: Production from economic reserves associated with mines that are currently in operation (as of 2021).

Economic reserves associated with projects under development: Production from economic reserves associated with mine projects that are under development (as of 2021).

Physical resources not associated with any mining project: Production from physical resources that are currently not associated with any economic reserves (i.e. not associated with any mine projects under development or in operation).

S2.2 Figures

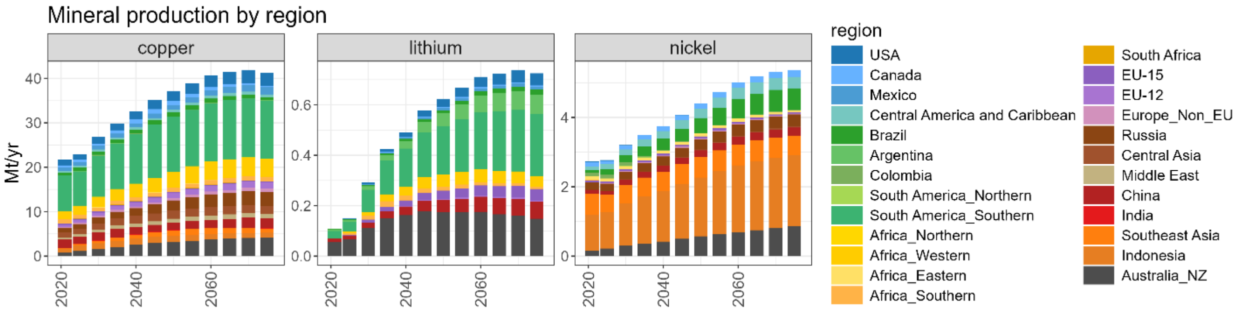

Figure S3. Annual primary mineral production by region in Mt/yr (2021-2075) in the *Reference* scenario.

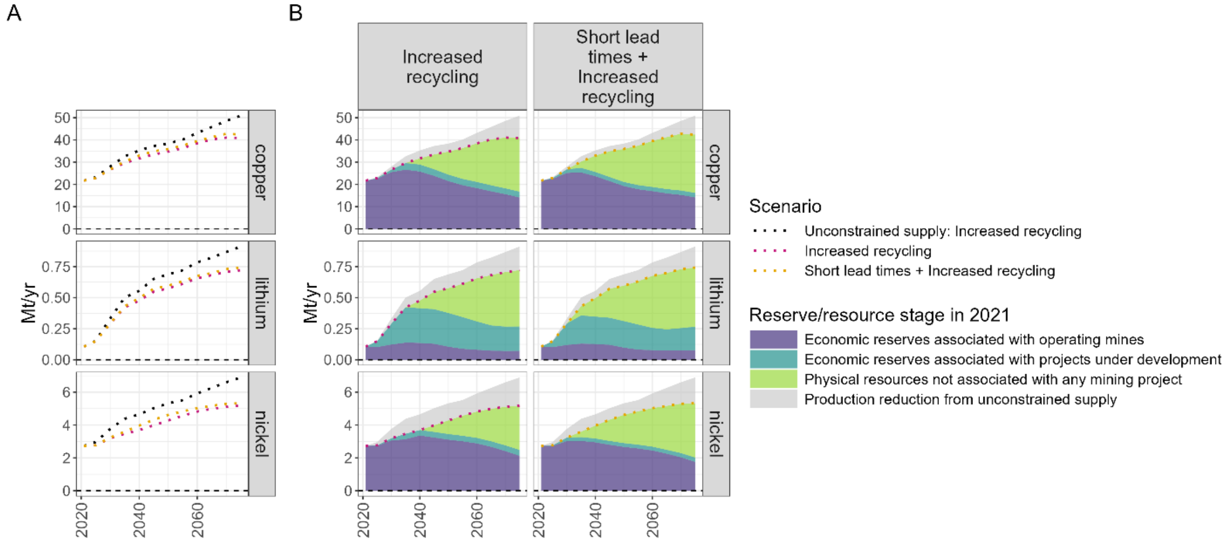

Figure S4. Global mineral production (2021-2075): supply-side dynamics (*Increased recycling* sensitivities). A) Annual mineral production (Mt/yr) across *Unconstrained supply: Increased recycling* and *Baseline constrained supply* (*Increased recycling* and *Short lead times* + *Increased recycling*) scenarios; B) Annual mineral production (Mt/yr) in the constrained supply scenarios, categorized by the development status of its associated reserves/resources as of 2021 (*colored area fill*). The grey area above the total annual mineral production (*solid line*) represents demand reductions in each scenario relative to the unconstrained supply scenario.

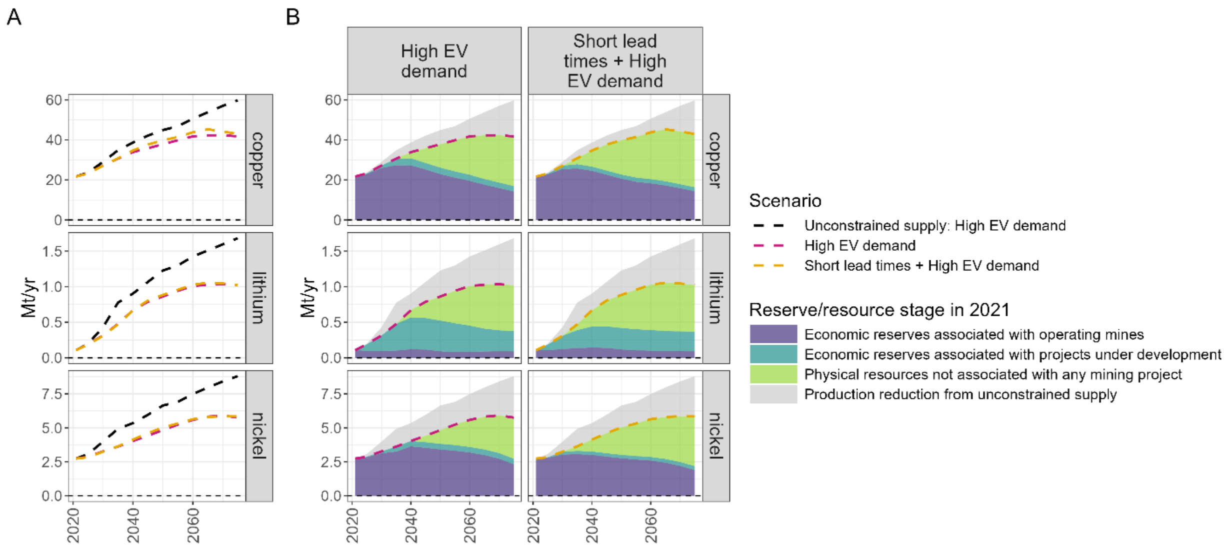

Figure S5. Global mineral production (2021-2075): supply-side dynamics (*High EV demand* sensitivities). A) Annual mineral production (Mt/yr) across *Unconstrained supply: High EV demand* and *Baseline constrained supply* (*High EV demand* and *Short lead times + High EV demand*) scenarios; B) Annual mineral production (Mt/yr) in the constrained supply scenarios, categorized by the development status of its associated reserves/resources as of 2021 (*colored area fill*). The grey area above the total annual mineral production (*solid line*) represents demand reductions in each scenario relative to the unconstrained supply scenario.

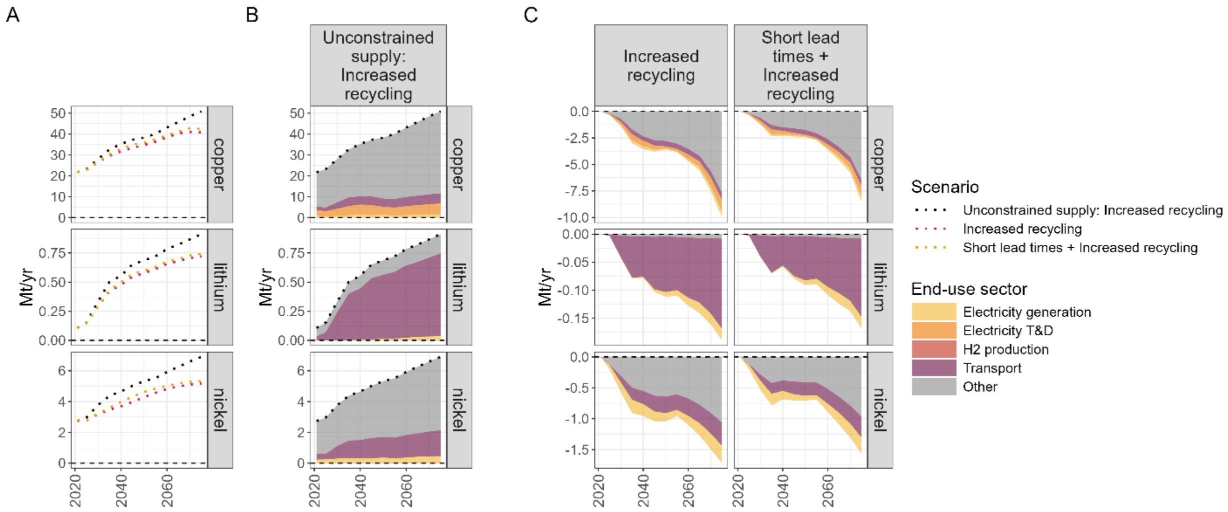

Figure S6. Global mineral consumption (2021-2075): demand-side dynamics (*Increased recycling* sensitivities). A) Annual mineral consumption (Mt/yr) across *Unconstrained supply: Increased recycling* and *Baseline constrained supply* (*Increased recycling* and *Short lead times + Increased recycling*) scenarios; B) Annual mineral consumption Mt/yr) in the *Unconstrained supply: Increased recycling scenario* (*solid line*), disaggregated into end-use demand sectors (*colored area fill*); C) Difference in annual consumption in each *Baseline constrained supply* scenario relative to *Unconstrained supply: Increased recycling* (Mt/yr), disaggregated into end-use demand sectors (*colored area fill*).

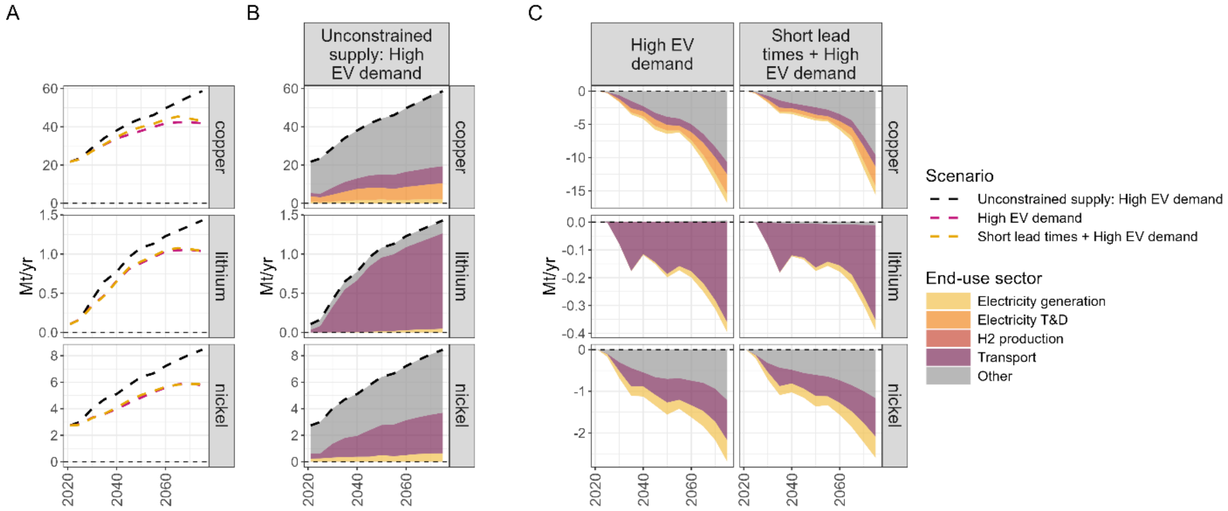

Figure S7. Global mineral consumption (2021-2075): demand-side dynamics (*High EV demand* sensitivities). A) Annual mineral consumption (Mt/yr) across *Unconstrained supply: High EV demand* and *Baseline constrained supply* (*High EV demand* and *Short lead times + High EV demand* scenarios; B) Annual mineral consumption Mt/yr) in the *Unconstrained supply: High EV demand scenario* (*solid line*), disaggregated into end-use demand sectors (*colored area fill*); C) Difference in annual consumption in each *Baseline constrained supply* scenario relative to *Unconstrained supply: High EV demand* (Mt/yr), disaggregated into end-use demand sectors (*colored area fill*).

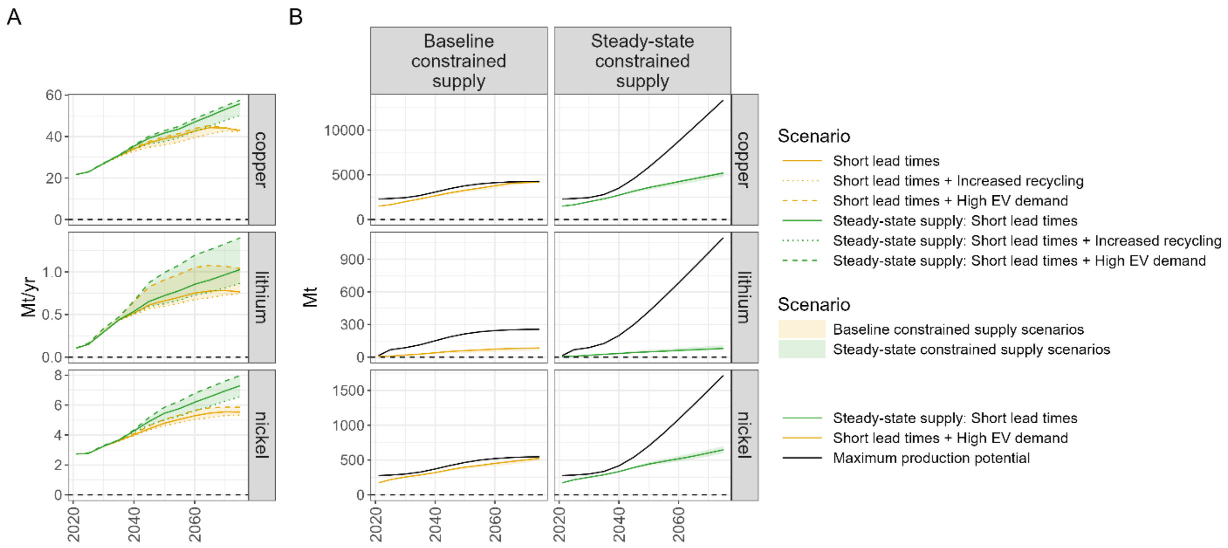

Figure S8. Global annual and cumulative mineral production: baseline versus steady-state constrained (2021-2075; *Short lead times* scenarios). A) Annual mineral production (Mt/yr) and B) Cumulative mineral production (Mt) across *Baseline constrained Supply: Short lead times (in yellow)* and *Steady-state constrained supply: Short lead times (in green)* scenarios. Each set *(ribbon)* includes *Baseline demand (solid line), High EV demand (dashed line), and Increased recycling (dotted line)* sensitivities. Panel B also contains the cumulative maximum production potential (Mt) for all scenarios in that facet plot (shown as a black solid line).

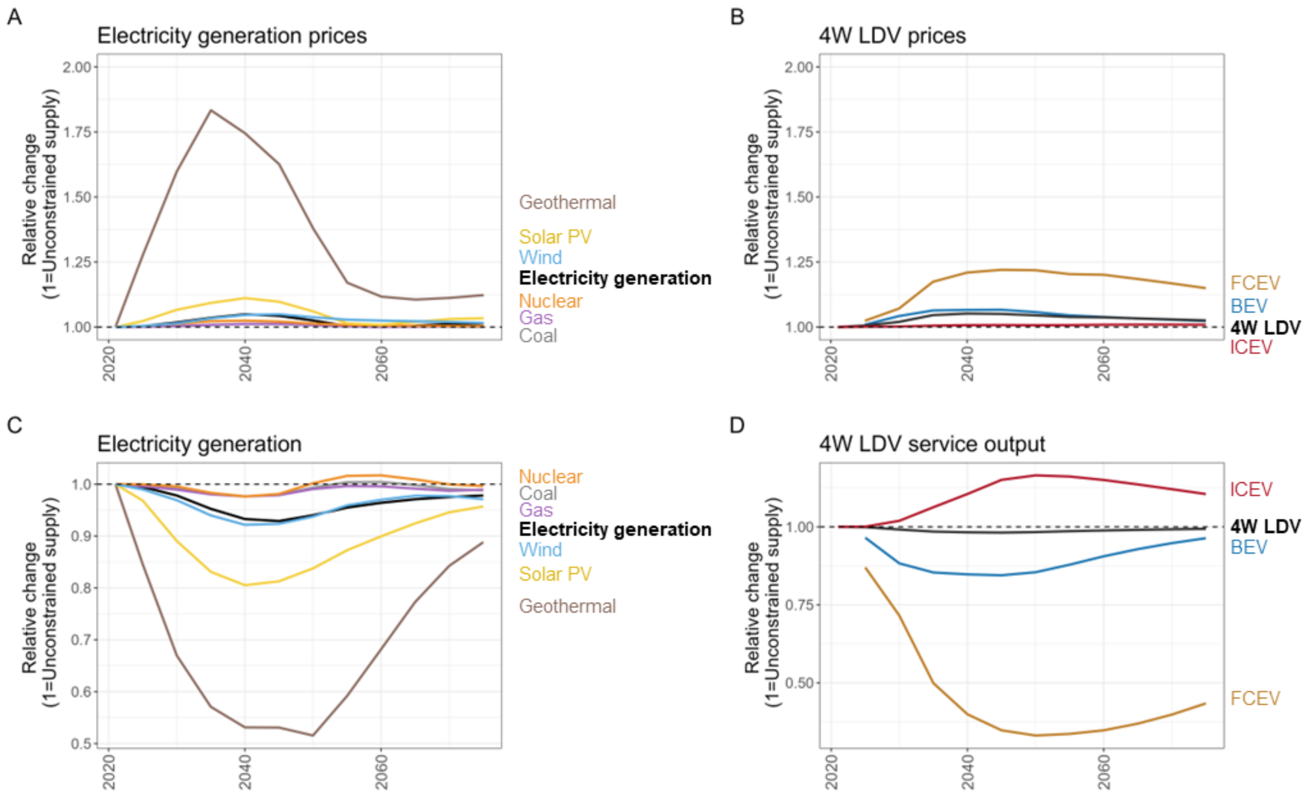

Figure S9. Global mineral prices changes and resulting impacts on the energy system (2021-2075) in *Steady-state supply* scenario. Relative changes compared to *Unconstrained supply* in the *Steady-state supply* scenario for C) Electricity generation prices; D) Four-wheeled light duty vehicle (4W LDV) service prices; E) Electricity generation; F) 4W LDV service output. In panels C-F, several example technologies (colored lines) along with the aggregate sector average across all electricity generation or 4W LDV technologies (black line) are shown. All prices and energy system changes reflect global weighted averages. For all panels, 1 = value in *Unconstrained supply* scenario. Note the difference in scale between the panels.

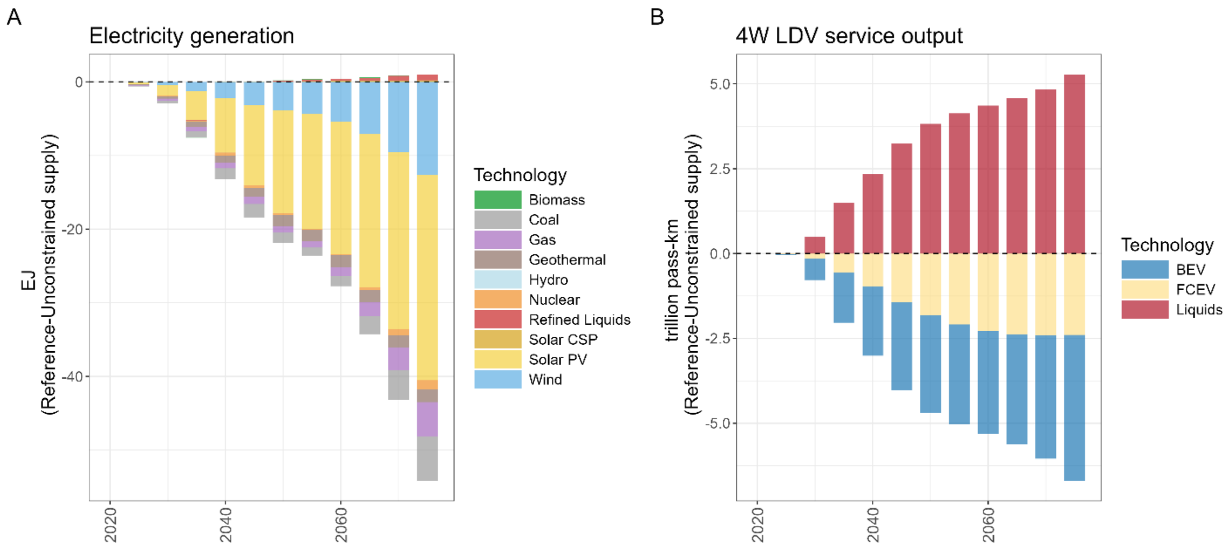

Figure S10. Absolute changes in A) electricity generation and B) 4W LDV service output under *Reference* compared to *Unconstrained supply*.

S3 Detailed methodology

S3.1 Global Change Analysis Model

GCAM has been developed and applied for several decades in major assessments of future energy system projections[27]. With the introduction of CMM demands for the electricity generation sector in Qiu et al. (2024)[28] and for transportation, electricity transmission and distribution, and hydrogen production sectors in Qiu et al. (forthcoming), GCAM now includes CMMs as one of its core interconnected sectors **(Figure S1).** In GCAM, the CMM sector is primarily connected to the energy system (in which CMMs are demanded), and socioeconomics (a key factor affecting the scale of energy system and CMM demand). In this study, we build upon GCAM version 8.2[29]. We have updated all prior critical minerals and materials demand-side developments to be compatible with this 8.2 model version.

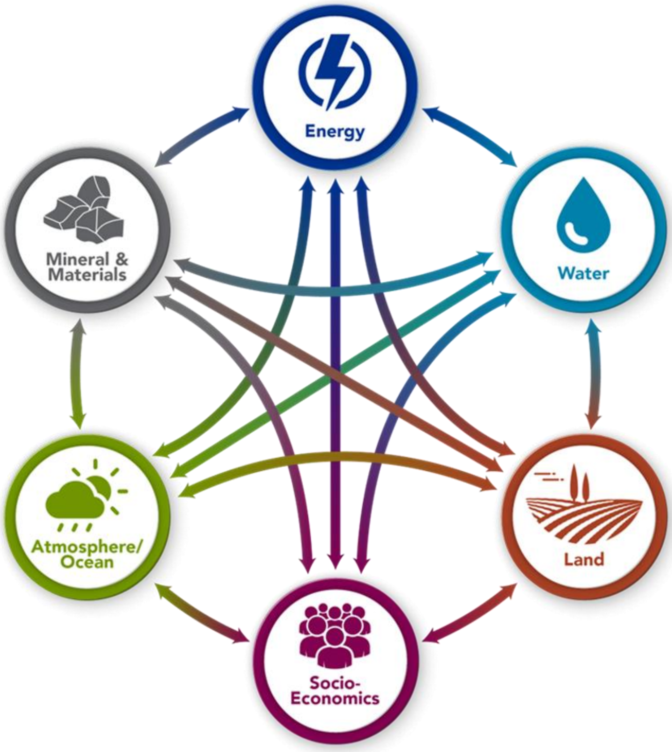

Figure S11. GCAM's interconnected multi-sectoral modeling framework.

S3.2 Supply curves

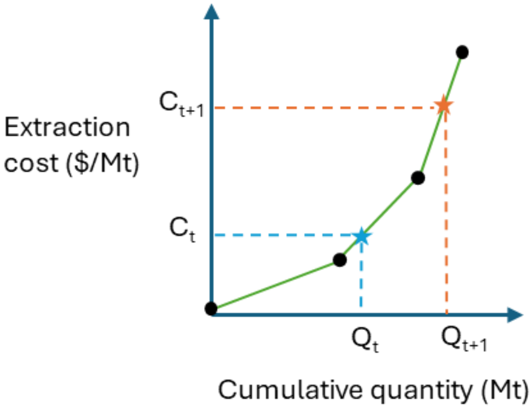

Figure S12. Example supply curve and cumulative mining cost calculation. In this figure, the green lines parametrize a graded supply curve, with black dots representing multiple grades. The blue star represents the point reached by time period *t*, while the orange star represents the point reached by time period *t+1*. The corresponding (Q, C) pairs indicate the cumulative quantity extracted and extraction cost by the specified time period. The total cumulative mining cost spent on mineral extraction by time period *t* is calculated as the area under the graded supply curve up to this point (Q_t, C_t).

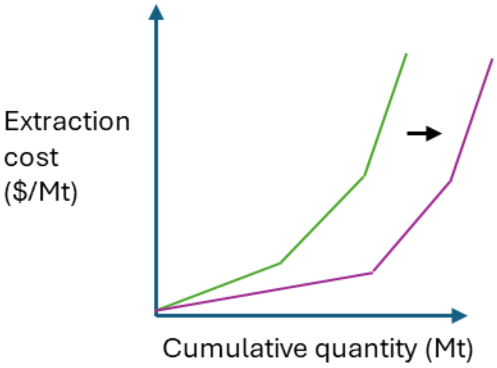

Figure S13. Example time-evolving supply curve. The green lines parametrize the supply curve in time period *t,* while the purple lines parametrize the supply curve in time period *t+1.* We illustrate the purple supply curve here as an incremental addition, or rightward shift from the green supply curve. However, within the model, we functionalize time-evolving supply curves in the model by having the incremental additional resource quantity that becomes available in each time period as its own subresource. For example, we define “copper” as a resource, with subresources “copper_2021”, “copper_2025”, etc., where the suffix in each subresource delineates the time period in which it becomes available, starting with the base year 2021. The sum of all subresource quantities accessible in each time period can be defined as the maximum production potential. For example, in 2030, the copper maximum production potential is equal to the sum of quantities in “copper_2021” + “copper_2025” + “copper_2030”.

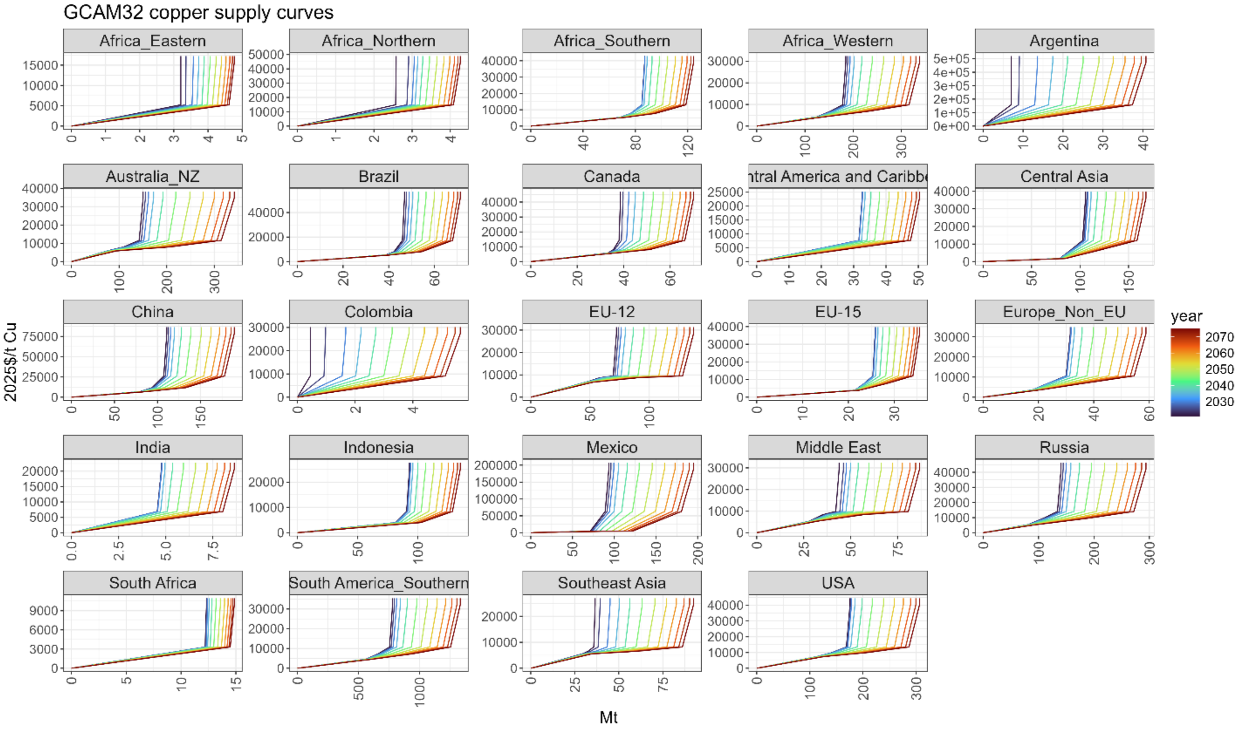

Figure S14. GCAM 32-region time-evolving copper supply curves (2021-2075) under *Baseline constrained supply*. Cumulative quantities are specified in Mt Cu, extraction costs specified in 2025$/tonne Cu. Cumulation starts from 2021, the model base year.

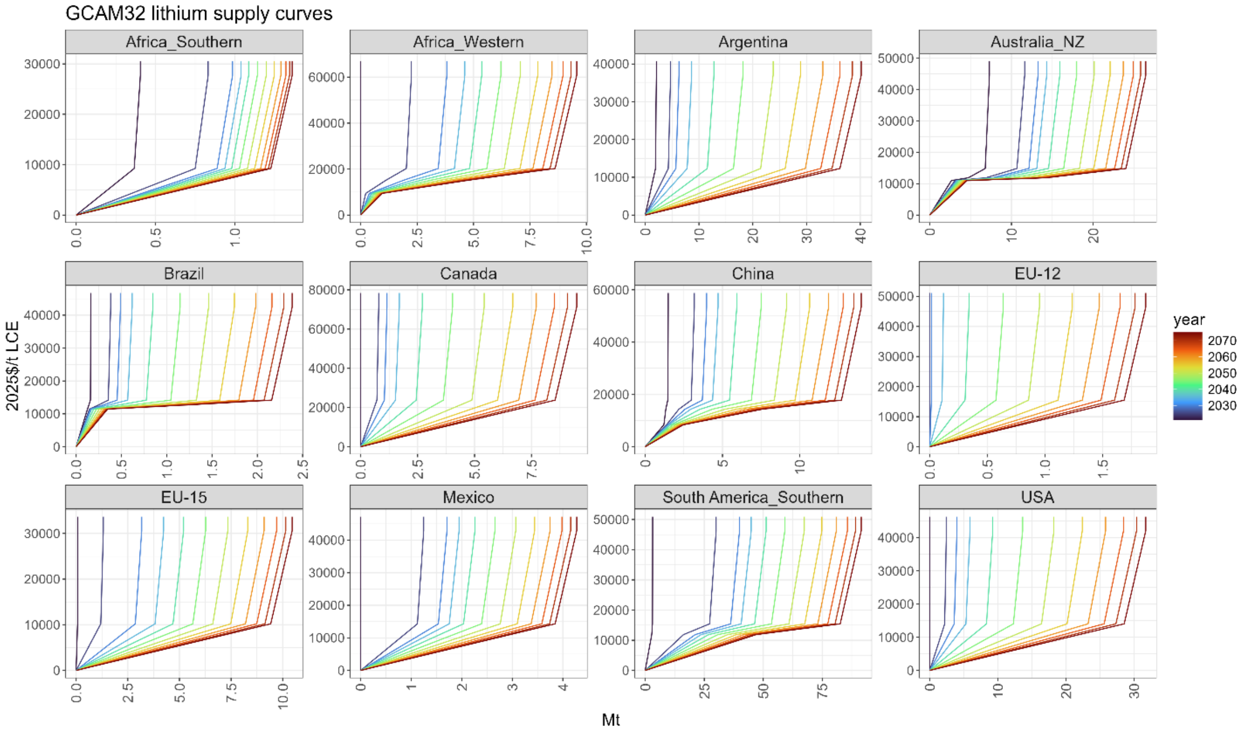

Figure S15. GCAM 32-region time-evolving lithium supply curves (2021-2075) under *Baseline constrained supply*. Cumulative quantities are specified in Mt Li, extraction costs specified in 2025$/tonne lithium carbonate equivalent (LCE). Cumulation starts from 2021, the model base year.

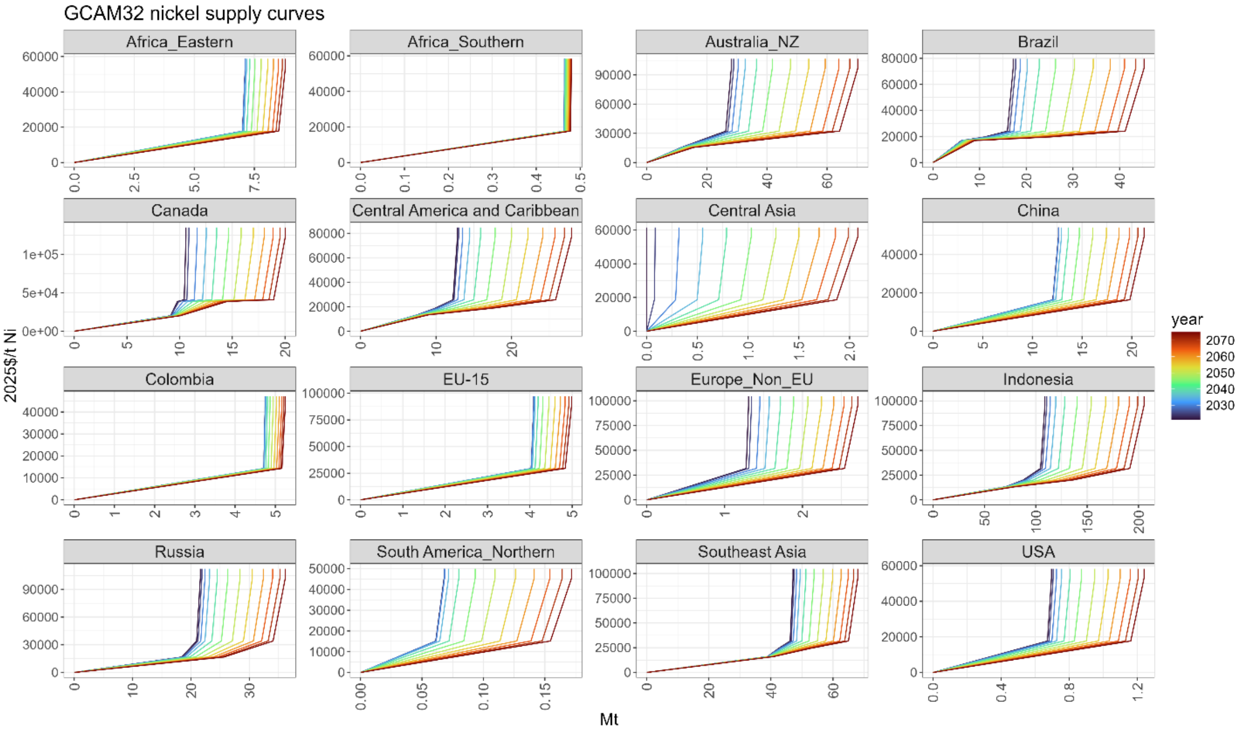

Figure S16. GCAM 32-region time-evolving nickel supply curves (2021-2075) under *Baseline constrained supply*. Cumulative quantities are specified in Mt Ni, extraction costs specified in 2025$/tonne Ni. Cumulation starts from 2021, the model base year.

S3.3 Lead times

		Copper		**Lithium**		**Nickel**	
Stage number	Stage	Reference	Short lead times	Reference	Short lead times	Reference	Short lead times
1	**Discovery**	4.1	3.0	4.3	3.1	3.9	2.8
2	**Early stage**	4.1	3.0	4.3	3.1	3.9	2.8
3	**Late stage**	4.1	3.9	4.3	3.1	3.9	2.8
4	**Incentive**	2.6	1.9	1.7	1.2	3.2	2.3
5	**Pre-production**	2.3	1.7	2	1.4	3.8	2.7
6	**Production**	0	0	0	0	0	0

Table S2. Lead time assumptions across stages for copper, lithium, and nickel. Based on assumptions from Manalo et al.[30].

We use an iterative function to calculate the quantity of resource Q in each stage i, in each future year t:

$$Equation\ S1.\ Q_{i,t} = Q_{i,t-1} * \left(1 - \frac{0.5}{lead\ time_i}\right) + Q_{i-1,t-1} * \left(1 - \frac{0.5}{lead\ time_{i-1}}\right)$$

S3.4 Mineral supply curve dataset synthesis

To generate a current snapshot of production capacity (Mt/yr) and resource quantity (Mt) in each development stage, we utilize two main datasets:

1. Proprietary data from S&P Capital IQ Pro Metals & Mining Data[31], providing a current snapshot of production capacity (Mt/yr) and resource quantity (Mt) of mine projects across development stages (i.e. operating, pre-production, undergoing feasibility studies, pre-feasibility scoping, etc), including only projects for which there were associated economic reserves.
2. Data from USGS Mineral Commodity Summaries[4], providing country-level *reserve* and *resource* totals (Mt).

The S&P data is the primary dataset providing a snapshot of resources across development stages, while the USGS aggregate resource and reserve data is used to fill known data gaps, correcting geographical bias in the S&P data and allowing us to align global total resources and reserves with USGS global totals. The following data synthesis steps were undertaken:

1. We first aggregated both datasets up to the 32 GCAM region level.
2. For each GCAM region, we took the larger value of total S&P or USGS reserves.
    a. For each GCAM region, if utilizing the S&P reserves, we used that region's defined levels of S&P reserves across each of the development stages.
    b. For each GCAM region, if utilizing the USGS reserves, we used the global split across development stages (based on S&P data for all regions) to assign USGS reserves across each of the development stages
3. The S&P data provides reserves across development stages spanning early stage to production, i.e. economic reserves that are already associated with mining projects. For each region, we added an additional stage representing "resources excluding reserves", based on USGS resource estimates. This represents physical resources that have not yet been associated with any mining project.
    a. For copper and nickel, we used USGS total global resource estimate (subtracting off reserves), and allocated these resources to each GCAM region on the bases of the regional share of reserves (in the prior development stages)
    b. For lithium, USGS provided country-level resource quantities, which we aggregated up to the GCAM region level, and used directly.

Our resulting synthesized dataset includes production capacities and resource/reserve quantities across development stages (from discovery to production stage), from which we could calculate time-evolving mineral resource quantities (as discussed above). This, alongside the extraction costs (obtained from S&P data) form the basis of the mineral supply curves used as input to the model.

S3.5 GCAM's production and reserve vintage structure

CMM production from reserves uses a vintage structure known as GCAM's resource-reserve model. GCAM's resource-reserve model was developed initially for fossil resources (coal, crude oil, natural gas), first added to the model in GCAM v5.2[32,33]. In this study, we apply the same resource-reserve functionality to modeling mineral resources (copper, lithium, and nickel). We note that GCAM's resource-reserve model uses the terms "resources" and "reserves" in a model-specific sense that differs from the mining industry definitions used in the main text. In the model, "resources" refers to the total available mineral pool (encompassing both economic reserves and physical resources as defined in the main text), while "reserves" refers specifically to the quantity of economic reserves that has been committed to active production capacity in the model. To avoid confusion, we will hereafter refer to these quantities as "resources/reserves" and "committed production reserves".

The resource-reserve model assumes that resources/reserves move into committed production reserves over time, and production occurs out of the quantity that is in committed production reserves. When new investments are made, resources/reserves are added to committed production reserves in the quantity needed for annual production multiplied by production lifetime. For example, if in the first time period, 2 Mt of copper production are needed, then, assuming a 50 year lifetime for this copper source, 100 Mt will be added to committed production reserves (2 Mt * 50 year lifetime). Additions to committed production reserves are made based on marginal investments needed. For example, in the second time period, if 3 Mt of copper production is needed, then 50 Mt would be added to committed production reserves (1 Mt marginal * 50 year lifetime), as the existing vintages from the previous time period will be assumed to continue to operate until their reserves are depleted.

S3.6 Additional parameters

Mine production lifetime

We calculate mine production lifetime for each GCAM region r as follows:

$$Initial\ mine\ prod.lifetime_r(yr) = \frac{\sum_{dev.\ stages} Resources/reserves_r\ (Mt)}{\sum_{dev.stages} Production\ capacity_r\ (\frac{Mt}{yr})}$$

This initial calculation may be an overestimate for some regions, because some regions do not have capacity for some stages. Therefore, for lifetimes above the median across regions, we simply used the median value.

Historical production

We initialize historical mineral production based on historical production data for copper, lithium, and nickel from USGS for GCAM historical years 1975-2021. We calculated historical committed production reserve additions to be exactly enough given historical production levels and our assumed mine production lifetimes for each region. We make this historical committed production reserve quantity available at in the base year (e.g. “copper_2021” subresource) at zero cost. Thus, we start calculating costs only from the first solved model period (2025) onward.

Calibrated prices

Analogous to the approach taken for GCAM’s fossil fuel resource prices, we initialize the copper, lithium, and nickel prices to USGS historical prices[34]. The model calculates a price “wedge” to absorb discrepancies between supply curve extraction cost and the calibration price. We phase this wedge out by 2100.

S3.7 Other sector demand representation

Calibration of base year other sector demands

For the USA region, we reviewed the literature to obtain bottom-up estimates of CMMs other sector demand in the base years, by calculating and subtracting off energy system demand from total demand. We subtracted the USA other sector demands from global other sector demands and allocated the remaining amount to all regions. Unless a specific value to calibrate base year other sector demand is available (currently only available for the USA region), other sector demand is assigned to regions on the basis of GDP.

Future projection of other sector demands

As the aggregate other sector does not contain explicit technologies, the following equation sets the rate of growth in each region r and time period t:

$$\begin{aligned} \textit{Equation S2.}\ \ & Other\ sector\ demand_{r,t} \\ & = Other\ sector\ demand_{r,t-1} * \left(\frac{pcGDP_{r,t}}{pcGDP_{r,t-1}}\right)^{\alpha} * \left(\frac{price_{t}}{price_{t-1}}\right)^{\beta} \\ & * (1 - Tech\ change) \end{aligned}$$

where income elasticity, α, is set to 1 for all CMMs following Fernandez (2018)[35] and price elasticity, β, is set to -1, to allow for a similar level of substitution in the other sector as compared to the energy system sectors (see **Figure S17**). Technological change rate of improvement is set to 0.5% annually, following the precedent in other GCAM sectors.

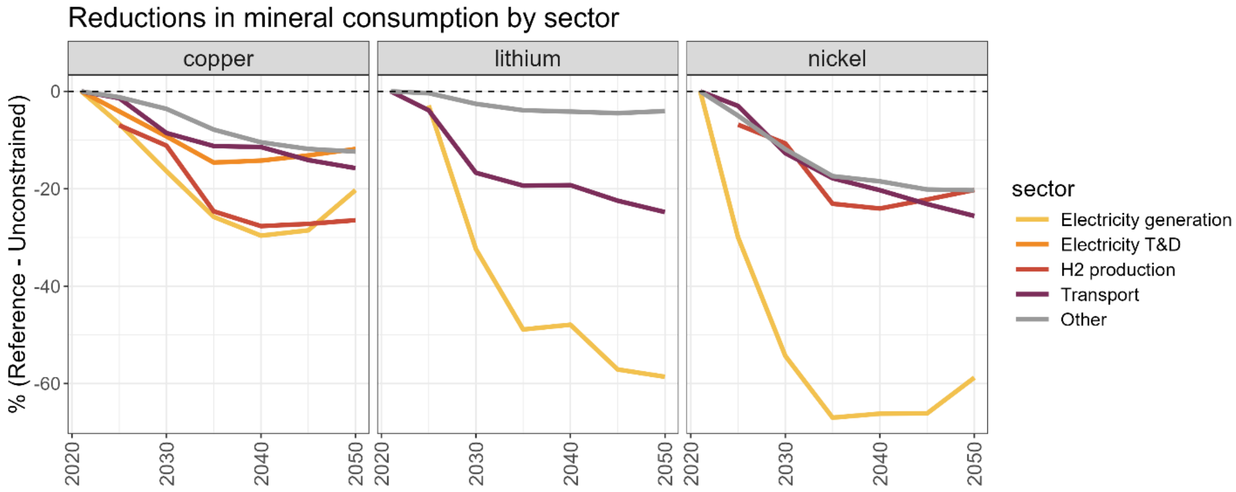

Figure S17. Relative substitutability across sectors (% change in mineral consumption by sector in the *Reference* scenario relative to *Unconstrained supply*).

S3.8 Mineral trade representation

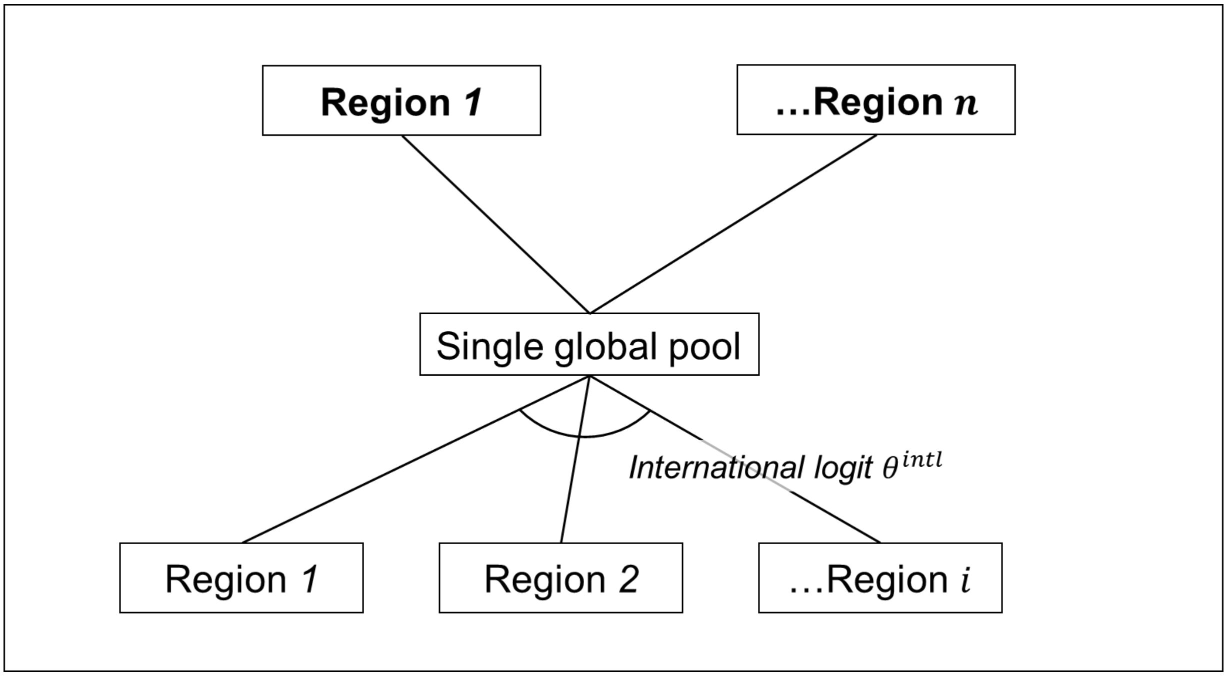

Figure S18. Minerals trade structure.

S3.9 Scenario parametrization

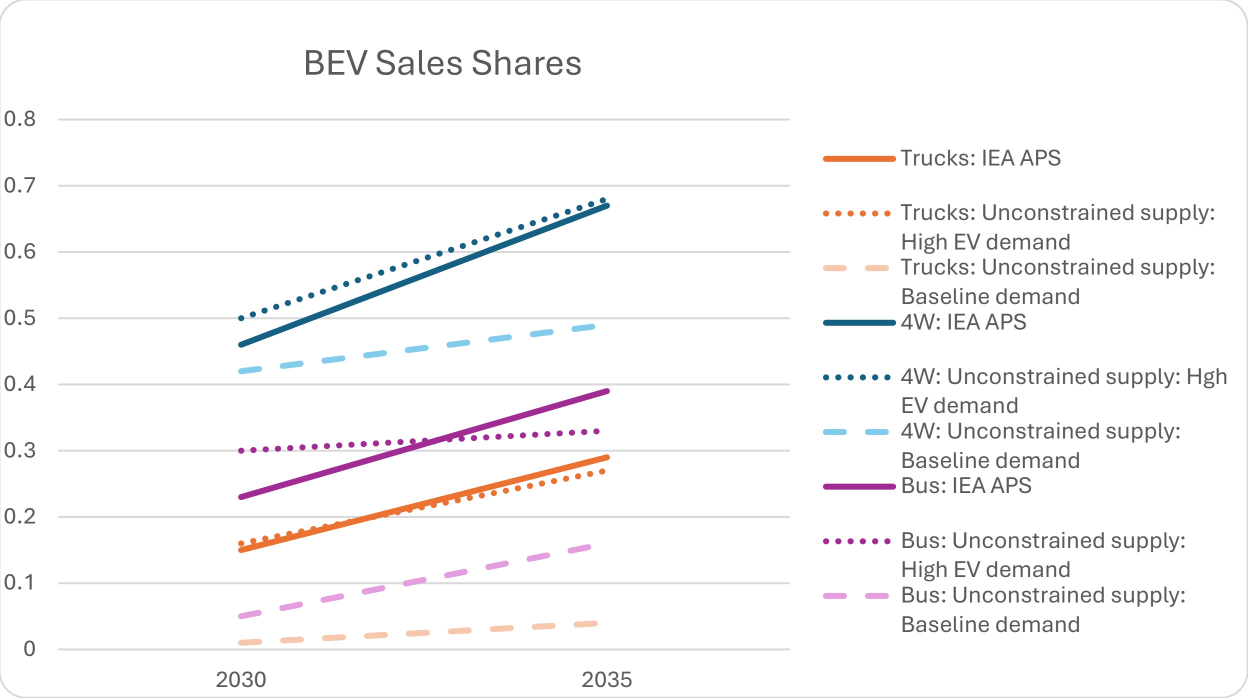

Figure S19. BEV sales shares by mode (trucks, 4W LDVs, and buses) in 2030-2035. Lines are shown for *Unconstrained supply: Baseline demand* (pale dashed lines), *Unconstrained supply: High EV demand* (dark dotted lines), and IEA APS scenario (dark solid lines).

References

1. IEA. *Global Critical Minerals Outlook 2025*. (2025).

2. Castillo, E. & Eggert, R. Reconciling Diverging Views on Mineral Depletion: A Modified Cumulative Availability Curve Applied to Copper Resources. *Resour. Conserv. Recycl.* **161**, 104896 (2020).

3. Calvo, G., Valero, A. & Valero, A. Assessing maximum production peak and resource availability of non-fuel mineral resources: Analyzing the influence of extractable global resources. *Resour. Conserv. Recycl.* **125**, 208–217 (2017).

4. Mineral Commodity Summaries | U.S. Geological Survey. https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries.

5. Northey, S., Mohr, S., Mudd, G. M., Weng, Z. & Giurco, D. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resour. Conserv. Recycl.* **83**, 190–201 (2014).

6. Elshkaki, A., Graedel, T. E., Ciacci, L. & Reck, B. K. Copper demand, supply, and associated energy use to 2050. *Glob. Environ. Change* **39**, 305–315 (2016).

7. Sverdrup, H. U., Ragnarsdottir, K. V. & Koca, D. An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity. *J. Clean. Prod.* **140**, 359–372 (2017).

8. de Koning, A. *et al.* Metal supply constraints for a low-carbon economy? *Resour. Conserv. Recycl.* **129**, 202–208 (2018).

9. Schipper, B. W. *et al.* Estimating global copper demand until 2100 with regression and stock dynamics. *Resour. Conserv. Recycl.* **132**, 28–36 (2018).

10. Watari, T., McLellan, B. C., Ogata, S. & Tezuka, T. Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios. *Minerals* **8**, 156 (2018).

11. Valero, A., Valero, A., Calvo, G. & Ortego, A. Material bottlenecks in the future development of green technologies. *Renew. Sustain. Energy Rev.* **93**, 178–200 (2018).

12. Fleming, M., Kannan, S. G. & Eggert, R. Long-run availability of mineral resources: The dynamic case of lithium. *Resour. Policy* **97**, 105226 (2024).

13. Busch, P., Chen, Y., Ogbonna, P. & Kendall, A. Effects of demand and recycling on the when and where of lithium extraction. *Nat. Sustain.* https://doi.org/10.1038/s41893-025-01561-5 (2025) doi:10.1038/s41893-025-01561-5.

14. Wu, F., Shivakumar, K. R., Konhauser, K. O. & Alessi, D. S. Lithium resources and novel strategies for their extraction and purification. *Npj Mater. Sustain.* **3**, 30 (2025).

15. Wesselkaemper, J. *et al.* Enhancing supply resilience for critical materials: case study of gallium supply in the United States. *Resour. Conserv. Recycl.* **222**, 108436 (2025).

16. Hache, E., Seck, G. S., Simoen, M., Bonnet, C. & Carcanague, S. Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport. *Appl. Energy* **240**, 6–25 (2019).

17. Ziemann, S., Müller, D. B., Schebek, L. & Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour. Conserv. Recycl.* **133**, 76–85 (2018).

18. Harvey, L. D. D. Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. *Appl. Energy* **212**, 663–679 (2018).

19. Sverdrup, H. U. Modelling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model. *Resour. Conserv. Recycl.* **114**, 112–129 (2016).

20. Vikström, H., Davidsson, S. & Höök, M. Lithium availability and future production outlooks. *Appl. Energy* **110**, 252–266 (2013).

21. Kushnir, D. & Sandén, B. A. The time dimension and lithium resource constraints for electric vehicles. *Resour. Policy* **37**, 93–103 (2012).

22. Elshkaki, A., Reck, B. K. & Graedel, T. E. Anthropogenic nickel supply, demand, and associated energy and water use. *Resour. Conserv. Recycl.* **125**, 300–307 (2017).

23. Olafsdottir, A. H. & Sverdrup, H. U. Modelling Global Nickel Mining, Supply, Recycling, Stocks-in-Use and Price Under Different Resources and Demand Assumptions for 1850–2200. *Min. Metall. Explor.* **38**, 819–840 (2021).

24. Zhang, Z., Zhang, W., Zhang, Z. & Chen, X. Nickel extraction from nickel laterites: Processes, resources, environment and cost. *China Geol.* **8**, 187–213 (2025).

25. Basuhi, R. *et al.* Clean energy demand must secure sustainable nickel supply. *Joule* **8**, 2960–2973 (2024).

26. Bradley, J. E. *et al.* System dynamics modeling of the global nickel supply system at a mine-level resolution: Toward prospective dynamic criticality and resilience data. *J. Ind. Ecol.* **29**, 1666–1683 (2025).

27. Horowitz, R. *et al.* The energy system transformation needed to achieve the US long-term strategy. *Joule* **6**, 1357–1362 (2022).

28. Qiu, Y. *et al.* The impacts of material supply availability on a transitioning electric power sector. *Cell Rep. Sustain.* **1**, (2024).

29. Bond-Lamberty, B. *et al.* JGCRI/gcam-core: GCAM 8.2. Zenodo https://doi.org/10.5281/zenodo.15581174 (2025).

30. Manalo. From 6 years to 18 years: The increasing trend of mine lead times. *S&P Global Market Intelligence* https://www.spglobal.com/market-intelligence/en/news-insights/research/from-6years-to-18years-the-increasing-trend-of-mine-lead-times (2025).

31. S&P Global Market Intelligence. S&P Capital IQ Pro Metals & Mining Data, Subscription. (2023).

32. Bond-Lamberty, B. *et al.* JGCRI/gcam-core: GCAM 5.2. Zenodo https://doi.org/10.5281/zenodo.3528353 (2019).

33. Edmonds, J. *et al.* Could congressionally mandated incentives lead to deployment of large-scale CO2 capture, facilities for enhanced oil recovery CO2 markets and geologic CO2 storage? *Energy Policy* **146**, 111775 (2020).

34. Mineral Commodity Summaries | U.S. Geological Survey. https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries.

35. Fernandez, V. Price and income elasticity of demand for mineral commodities. *Resour. Policy* **59**, 160–183 (2018).