

Critical Mineral and Material Supply Availability and Energy System Development: A Multisector Analysis and Implications

Yang Qiu

yang.qiu22@pnnl.gov

Pacific Northwest National Laboratory <https://orcid.org/0000-0003-4772-5079>

Brinda Yarlagadda

Pacific Northwest National Laboratory

Neal Graham

Pacific Northwest National Laboratory

Matthew Binsted

Pacific Northwest National Laboratory

Pralit Patel

Pacific Northwest National Laboratory

Marshall Wise

Pacific Northwest National Laboratory

Allen Fawcett

Pacific Northwest National Laboratory

Maggie Liu

Pacific Northwest National Laboratory

Siddarth Durga

Pacific Northwest National Laboratory

Nathan Wiens

Pacific Northwest National Laboratory

Anastasiia Zagoruichyk

Pacific Northwest National Laboratory

Gokul Iyer

Pacific Northwest National Laboratory

Research Article

Keywords:

Posted Date: July 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10492347/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Critical Mineral and Material Supply Availability and Energy System Development: A Multisector Analysis and Implications

Yang Qiu^{1,*}, Brinda Yarlagadda¹, Neal Graham¹, Matthew Binsted¹, Pralit Patel¹, Marshall Wise¹, Allen Fawcett¹, Maggie Liu¹, Siddarth Durga¹, Nathan Wiens¹, Anastasiia Zagoruichyk¹, Gokul Iyer¹

1. Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Maryland, USA, 20740

* Author to whom any correspondence should be addressed.

Corresponding Author E-mail: yang.qiu22@pnnl.gov

Abstract

Critical minerals and materials are essential to energy systems and the broader economy, yet securing adequate supply amid rapidly rising demand faces physical and geopolitical challenges. We enhance the Global Change Analysis Model to endogenously represent material demand across multiple energy sectors and assess the multisector implications of material supply availability. Results show that material production constraints generate system-wide impacts through cross-sector interdependencies, with changes in one sector propagating throughout others in the system, affecting technology deployment, energy service demand, and prices. Halving 2050 bulk material production (i.e. steel, aluminum, and copper) relative to an unconstrained scenario increases U.S. electricity prices by 39%–70% and electric vehicle service costs by 36–85%. Equivalent constraints on specialty materials (e.g., lithium, neodymium, platinum, etc.) raise those costs by up to 11% and 40%, respectively. These findings highlight the importance of integrated, economy-wide approaches to understanding the energy–materials nexus under supply risk.

Introduction

Critical minerals and materials (CMMs) are fundamental to the development of many sectors in the global economy, including energy, transportation, and others. The rapid expansion of these sectors is expected to substantially increase the demand for a wide range of CMMs in the coming decades^{1,2}. However, ensuring a stable and secure supply of these materials to meet rapidly growing demand faces multiple challenges. These include long lead times for mine development^{3,4}, increasing geopolitical and trade risks⁵, high concentration of mining and refining in a few countries⁶, and concerns about environmental and social impacts^{7,8}. Such challenges raise concerns about the availability, affordability, and security of critical minerals, with potential implications for the pace and cost of global energy system evolution^{9,10}.

Existing studies have estimated future material demand across key energy sectors under various socioeconomic and energy system development scenarios^{11–14}. More recent analyses have explored how material price changes^{15–17} or production constraints^{18–20} might influence specific sectors or technologies. However, these analyses examine the impacts of material supply constraints on technologies within a single-sector context, limiting the ability to capture cross-sectoral linkages and their competition for finite CMM supply. Sectors such as electricity generation, transportation, and industry are deeply interconnected through material and energy uses¹¹. Hence, analyzing one sector in isolation overlooks these interdependencies and may bias the results. Therefore, there is a need to understand how constraints on CMMs propagate through multiple economic sectors and identify which sectors are more resilient or more exposed^{2,21}. Such understanding can provide important insights to inform management of risks. Our study addresses the need for a multisectoral perspective on CMMs.

The primary objective of this study is to examine how material supply availability influences energy-related sectors, with a focus on sectoral material demand, technology deployment, and associated service output and costs. Specifically, we first quantify the future global material demand from multiple sectors. These sectors include electricity (both generation and transmission & distribution (T&D)), transportation, and hydrogen production. Second, we evaluate how production constraints of each material may affect the demand for other materials and its own demands across different sectors. Third, we analyze how these constraints influence technology deployment: characterizing the material–energy nexus at both sectoral and technological levels and evaluating the resulting implications for sectoral service output (i.e., electricity generation, passenger/freight travel, hydrogen production) and costs.

We accomplish these objectives by building on our previous work and expanding the capability of the Global Change Analysis Model (GCAM)^{19,22}—a state-of-the-art, integrated, multisector model—to represent material demands across key end-use sectors (i.e. electricity, transportation, and hydrogen production). A detailed method of modeling material demand from these sectors is provided in **Supplementary Note 1**. We consider a total of 13 materials in this study. These include three bulk materials—steel, aluminum (Al), and copper (Cu)—which are industrial metals with broad cross-sectoral applications and high production volume. The remaining ten are specialty materials: silicon (Si), lithium (Li), graphite, cobalt (Co), nickel (Ni), manganese (Mn), neodymium (Nd), tellurium (Te), vanadium (V), and platinum (Pt). Compared with bulk materials, these specialty materials serve technology-specific functions and generally have lower global production volumes. These 13 materials are included due to their importance to the development of modern energy technologies and the potential supply uncertainties with many of them. Using this enhanced modeling framework, we estimate future material demand across multiple sectors and explore how constraints on material supply availability could affect sectoral development.

We design a suite of exploratory scenarios to evaluate how material supply availability might influence sectoral material demand, technology deployment, and associated service output and costs. All scenarios follow a business-as-usual energy system development, which assumes future development largely based on relative economics starting from current trends but without any additional policy interventions. The key variation across scenarios lies in the material supply availability. The *Central scenario* assumes no constraint on annual production of all 13 materials, and it serves as the reference to compare other scenarios against. By contrast, the *Constrained scenarios* impose exogenous, sector-specific, annual production constraints on each of the materials. Because material demand accounting in GCAM currently covers a subset of end-use sectors, the production constraints are designed to limit future material supply for three energy sectors: electricity (both generation and T&D), transportation, and hydrogen production. For each material, we construct the constraint by interpolating from the estimated 2025 demand (for these three sectors) to alternative 2050 production levels set at 25%, 50%, and 75% of the corresponding 2050 demand in the *Central scenario* (**Table 1**). These alternative 2050 levels represent varying degrees of supply stringency, enabling us to evaluate how uncertainty in material availability affects model outcomes.

In GCAM, the annual production constraints of materials affect technology deployment by generating an endogenous shadow price, which reflects the marginal value of the constrained material. This shadow price raises the material price, which increases technology costs, reduces their cost competitiveness, and ultimately lowers deployment so that material demand and supply remain in equilibrium. These exploratory scenarios provide a broad range of potential supply conditions, allowing us to assess how varying degrees of material scarcity influence the future evolution of key sectors. By applying the same levels of constraints across materials, we can also compare their relative impacts on different technologies and identify which materials exert the

greatest influence on technology deployment and sectoral outcomes. This approach further enables us to examine potential nonlinear effects of supply availability on sectoral service output and cost.

Results

Multi-sector demand for critical minerals and materials

Our results show that energy system expansion and technology deployment drive the future demand growth of the 13 materials in the modeled energy sectors (i.e. electricity, transportation, and hydrogen production). In the *Central scenario*, total global material demand from these sectors increases by a factor of 1.6 (steel) to 5.5 (Li) from 2025 to 2050. The electricity and transportation sectors dominate demand for nearly all materials.

Within the modeled energy sectors, Cu demand is driven not only by electricity generation and transportation but also by substantial needs in electricity T&D. By 2050, T&D alone is projected to require 7.7 Mt of Cu, about 40% of demand from these energy sectors. Li, graphite, Co, Ni, and Mn, with their applications in Li-ion batteries, see rapidly rising demand due to the adoption of battery electric vehicles (BEVs). Beyond batteries, the increasing demands of Ni and Mn are also due to their role in steel alloys used in vehicle and energy technology manufacturing. Nd demand grows with the use of Neodymium-Iron-Boron (NdFeB) permanent magnets in wind turbines and transportation applications. V demand reflects both its use in steel alloys and its emerging role in vanadium flow batteries; the latter becomes the dominant source of V demand by 2050, raising total V demand (from electricity and transportation sectors combined) to ~0.1 Mt, which is approximately equal to 2024 global production of V. Pt demand is overwhelmingly driven by the adoption of fuel cell electric vehicles (FCEV), reaching 0.66 kt in 2050, while Pt needs in hydrogen

production remain comparatively small because electrolyzers use much less Pt and hydrogen production continues to be dominated by steam methane reforming, which does not require Pt.

Overall, GCAM's projected material demands are broadly comparable to other published estimates, particularly for the electricity and transportation sectors. Differences remain in certain emerging sectors, reflecting variations in technology deployment pathways and modeling assumptions across studies. A detailed comparison of material demand estimates is provided in **Supplementary Note 3**.

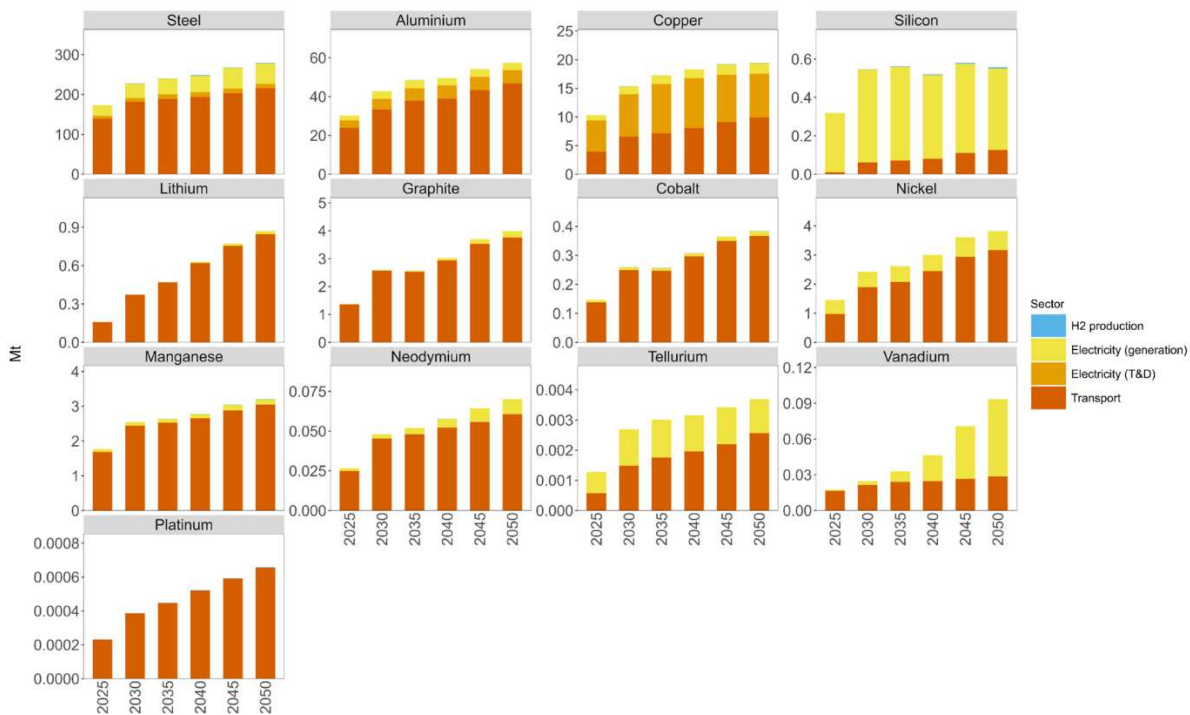


Figure 1. Global material demand across sectors under *Central scenario* (no constraint on material annual production)

Effects of individual material production constraint on demand for other materials

Constraints on individual materials can affect the demand for other materials through technology linkages and substitution effects. Constraints on bulk materials (i.e., Steel, Al, and Cu) have particularly broad impacts, reducing demand for nearly all other materials. For example, a 50%

production constraint on steel reduces the demand for all other materials, with percentage declines ranging from 17% to 72%. Similar patterns are observed for Al and Cu, and production constraints on them also lead to widespread reductions in demand for other materials. This occurs because bulk materials are widely used across broad end-use technologies. Production constraints on these materials limit new deployments across many technologies, thereby reducing demand for other associated materials.

There are also interdependencies among materials primarily used in battery technologies, such as Li, graphite, and Co. Production constraints on one these materials lead to reductions in demand for rest of them, largely due to decreased deployment of battery storage and BEVs under the corresponding *Constrained scenarios*.

Some demand changes are also driven by technology substitution. For example, a 50% production constraint on Si results in a 38% increase in Te demand. This is because Si constraint limits the deployment of crystalline silicon photovoltaic (c-Si PV), leading to greater deployment of cadmium telluride photovoltaic (CdTe PV), which increases Te demand. Similarly, substitutions occur between battery-related materials (e.g., Li, graphite, and Co) and Pt (which is primarily used in hydrogen production technologies, like electrolysis, and fuel-cell electric vehicles (FCEVs)). For example, 50% production constraints on Li and graphite increase Pt demand by 8% and 10%, respectively. This occurs because constraints on Li and graphite limit BEV deployment in the transportation sector, increasing reliance on alternative technologies, including hydrogen-based systems. As a result, deployments of FCEVs and electrolysis hydrogen production technology increase, leading to higher Pt demand.

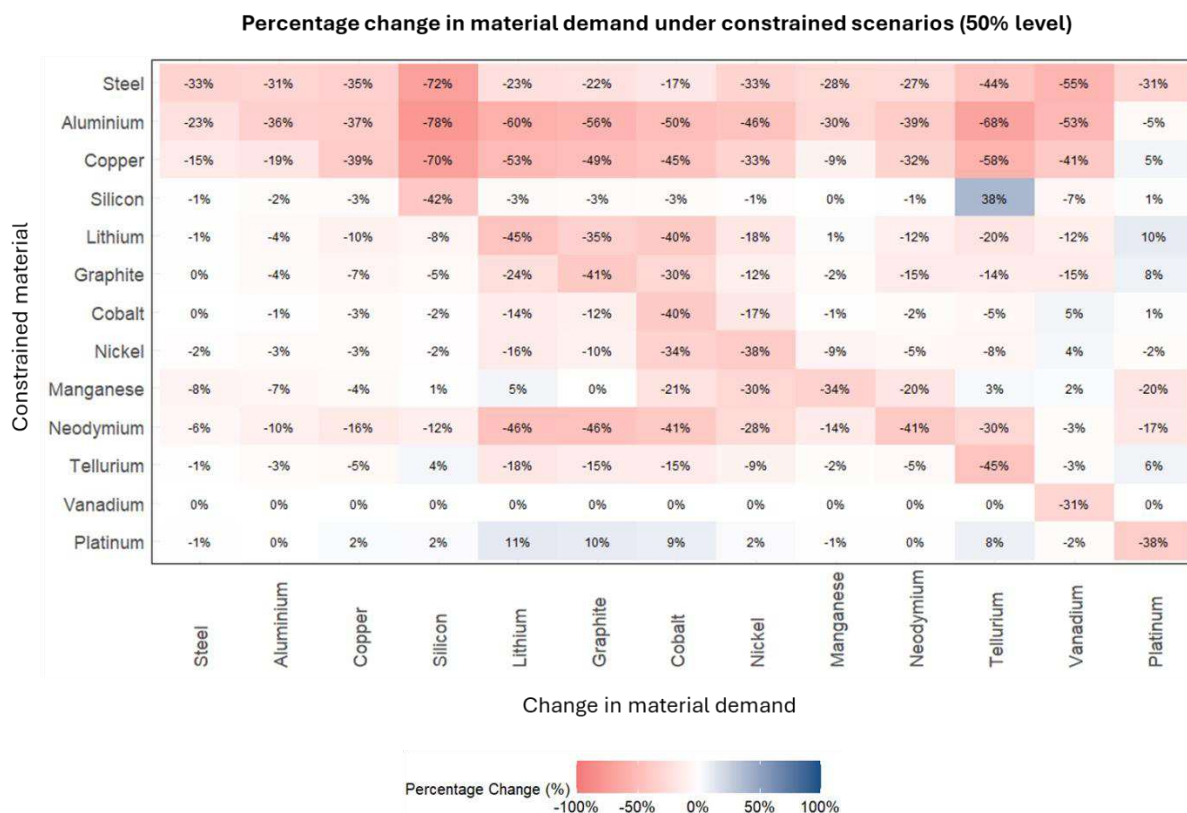


Figure 2. Percentage change of material demand under *Constraint scenarios* at 50% level. Results calculated based on cumulative demand of each material (from electricity, transportation, and hydrogen production sectors) from 2025 to 2050. Each row represents a constrained scenario, where the row label indicates the material subject to the production constraint. Value > 0 implies an increase in demand relative to the *Central scenario*, while value < 0 implies a decrease in demand relative to the *Central scenario*. Note: the percentage change in the diagonal of the heat map is not exact 50% reduction. This is due to the constraint assumption we made. Under production constraint at 50% level, we assume that the 2025 value of the constraint (equal to 2025 demand in *Central scenario*) is linearly interpolated to 2050 which is equal to the 50% 2050 demand in the *Central scenario*. Therefore, under 50% material constraint level, the reduction of cumulative demand during 2025 and 2050 may not be exact 50%. A figure showing the estimated material demand projections under *Central scenario* and production constraint trajectories are showing in **SI-Figure 2**. The percentage change results of material demand for each sector (50% production constraint level) are showing in **SI-Figure 3-5**.

Impacts of production constraints on sectoral material demand

Under material production constraints, sectoral demand responds differently depending on substitution flexibility and material intensity. When 50% production constraints are applied to bulk materials such as steel, Al, or Cu, demand for these bulk materials in the power generation sector declines more sharply (by 75%, 77%, and 71% respectively) compared to their demand reductions in the transportation sector (by 23%, 32%, and 28% respectively) (**Figure 3**). This contrast reflects differences in substitution potential across sectors. Because bulk materials are used widely across many technologies, their production constraints have broad system-level impacts. Electricity generation is embedded in a broader energy transformation system in which multiple energy carriers contribute to overall energy supply. When constraints on bulk materials limit the deployment of material-intensive power technologies, particularly renewable generation, energy supply can shift toward alternative, less material-intensive energy transformation pathways outside the electricity sector. This reallocation reduces the need for new power capacity expansion and, consequently, lowers bulk material demand in the electricity sector. In contrast, the transportation sector provides mobility services with limited cross-sector substitution options, leading to smaller proportional demand reductions of the bulk materials than those observed in the electricity generation sector.

For other materials with specialized applications, adjustments in material demand are driven primarily by the share of the material cost in total technology capital costs (which essentially reflect the technology material intensity). Specialty materials such as Li and graphite are predominantly used in Li-ion batteries, which serve both utility-scale energy storage in the power sector and BEVs in transportation. Because Li and graphite account for a larger cost share in grid-scale battery systems than in BEVs (**SI-Figure 6**), rising prices of these materials under production constraints

lead to larger reductions in battery storage deployment in the power sector. As a result, Li and graphite demand fall by 73% and 81%, respectively, in the power sector, which are much higher than the corresponding demand changes (45% and 40%, respectively) in transportation. Similar patterns emerge for other specialty materials (e.g., Si, Ni, Nd, Pt, etc) with concentrated technological uses are also driven by differences in material intensities in the applied technologies.

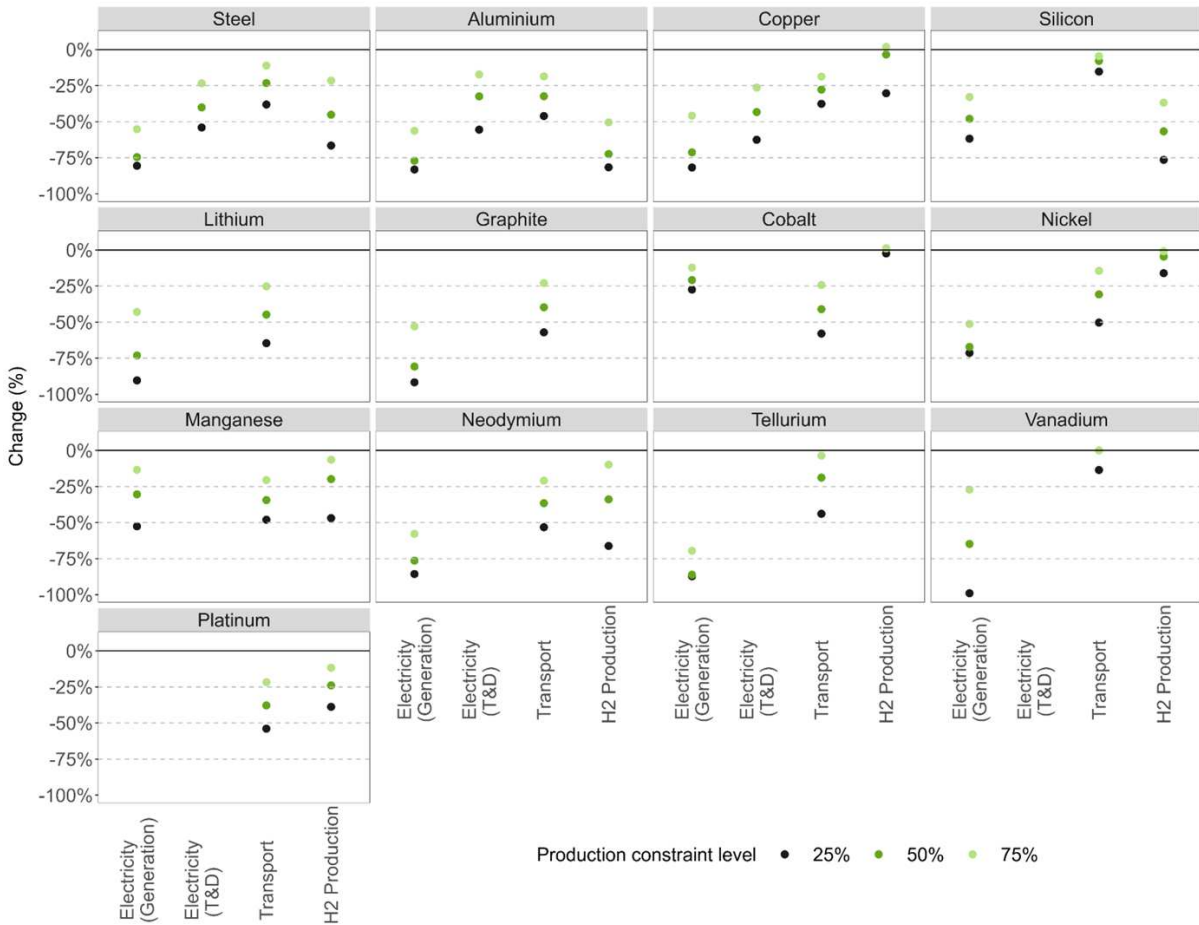


Figure 3. Changes in sectoral material demand under material production constraints. In each panel, the production constraints are applied to one material, and the dots represent the relative change (%) of sectoral material demand (under different production constraint levels) compared to the *Central scenario*. Results are calculated based on cumulative demand (from 2025 to 2050) for each sector.

Impacts of production constraints on technology deployment

The interdependence between material availability and technology deployment—the material–technology nexus—is shaped by how they are used in energy system technologies. As a result, production constraints on different materials can have different impacts on technology deployment.

In the power sector, technology responses vary under material constraints. Fossil-based generation technologies (coal, gas, and oil) are primarily affected by bulk material constraints. When steel, Al, or Cu are constrained to 50% level, new capacity additions of the fossil-based generation technologies together decline by 43%, 31%, and 49%, respectively (**Figure 4**). Renewable and storage technologies together experience even larger reductions—by 81%, 56%, and 72%—because of their higher material intensities. Several specialty materials also exert strong influences due to their unique technological applications. For instance, geothermal systems depend heavily on Ni-based steel alloys for corrosion-resistant piping, and Ni constraints lead to a 72% decline in geothermal capacity. Similarly, Si, Nd, and battery-related minerals (Li, Ni, Co, graphite, and Mn) are essential for c-Si PV, wind turbines, and battery storage, so constraints on these materials substantially reduce deployment of these technologies, respectively.

Such constraints also induce technology substitution toward less material-intensive alternatives—for example, Si constraints reduce c-Si PV capacity by 46% while increasing CdTe and CIGS PV deployment by 108% and 104%, respectively. Nd constraints reduce most wind subtype technologies but favor the subtype wind technology based on gearbox with a doubly fed induction generator (GB-DFIG), which requires minimal Nd compared to other subtypes.

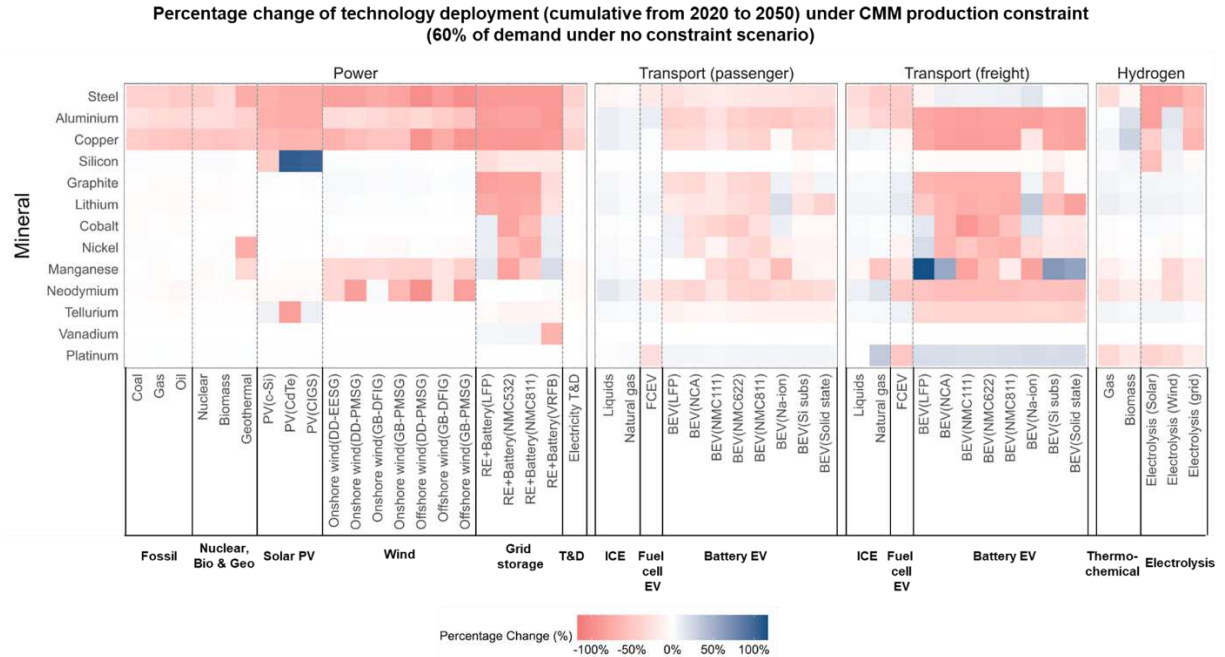


Figure 4. Heatmap showing the impact of material production constraints (under 50% level) on new technology deployment (cumulative from 2025 to 2050) in different sectors. Each row represents one *Constrained scenario*, which applies annual production constraint at 50% level to one material. The column represents individual technology. Value > 0 implies increased new deployment under a material production constraint, while value < 0 implies decreased new deployment under a material production constraint. A detailed explanation on technologies represented in different sectors can be found in **Supplementary Note 1** and **SI-Table 1 to SI-Table 3**.

In the transportation sector, material constraints primarily reduce BEV deployment and shift the new deployment toward internal combustion engine (ICE) vehicles, which are generally less material-intensive. Constraints on Li-ion battery-related specialty materials reshape the mix of BEV subtypes. Under Li constraints, all Li-ion BEV variants decline by 18–40% for light-duty passenger vehicles and 48–81% for freight trucks, while BEVs using sodium-ion (Na-ion) battery rise by 20% and 33% as substitutes for the two modes. Similarly, Co constraints reduce the deployment of Co-containing BEV subtypes but increase the shares of Co-free or low-Co options such as BEV (with lithium iron phosphate (LFP) battery) and BEV (with Na-ion battery). Pt constraints sharply reduce FCEV deployment—by 28% for light-duty passenger vehicles and 49% for freight trucks—while

inducing compensating increases in BEV deployment of roughly 6% and 21% for light-duty passenger vehicles and freight trucks, respectively.

In the hydrogen production sector, constraints on bulk materials reduce deployment of hydrogen production technologies overall and shift capacity toward less material-intensive alternatives such as biomass-based hydrogen. Specialty materials—including Nd and Pt—also substantially reduce hydrogen production capacity (by roughly 20% and 27%, respectively), particularly affecting electrolysis systems. These impacts arise not only from the direct effect of material constraints on hydrogen production technologies but also from indirect system interactions. For example, Nd and Pt constraints suppress FCEV deployment in the transportation sector, lowering hydrogen demand and further reducing hydrogen technology deployment.

Impacts of production constraints on service output.

Material constraints affect sectoral service outputs (i.e., electricity generation, passenger/freight travel, hydrogen production), but the magnitude and direction of impacts vary by both material type and sector. The constraints on bulk materials lead to the largest reductions in electricity generation because they are required across nearly all generation technologies and T&D networks. When steel, Al, and Cu are constrained to 50% levels, global electricity generation in 2050 decreases by 43%, 31%, and 41%, respectively (**Figure 5**). In contrast, constraints on specialty materials tend to have smaller system-wide effects. For example, since Si is used only in c-Si PV; under a Si constraint, the reduction in c-Si PV output is partially offset by substitution toward thin-film PV technologies (e.g., CdTe PV and CIGS PV), resulting in limited impact on overall electricity generation. Similarly, constraints on Li and graphite—primarily used in Li-ion batteries—also have minor impacts on total electricity generation. This is because battery deployment in the power sector is smaller relative to other technologies, and alternative storage technologies, such as vanadium flow batteries, partially

compensate for reduced electricity output from Li-ion battery. Mn and Nd constraints have more pronounced impacts compared to other specialty materials, reducing 2050 electricity generation both by up to 7% under a 50% production constraint of these materials, as both materials are heavily used in wind turbines (structural steel additives for Mn and NdFeB magnets for Nd).

Similar patterns emerge in the transportation sector. With production constraints on steel, passenger travel for both BEVs and ICE vehicles reduces because steel intensities of these two types of vehicles are relatively similar. In contrast, Al and Cu constraints disproportionately affect BEVs due to their higher intensities in BEV drivetrains, therefore the cost of BEV is more sensitive to price hike of Al and Cu under these scenarios, leading to a shift in passenger travel toward ICE vehicles. Constraints on Li-ion battery related materials—Li, graphite, Ni, and Co—generally decrease passenger travel of BEV while increasing that of ICE vehicle through substitution. However, the presence of multiple BEV battery chemistries helps alleviate the overall impact. For example, Li constraints reduce passenger travel for all Li-ion BEV variants, but Na-ion BEVs increase to offset part of the loss. Graphite constraints reduce passenger travel for most Li-ion BEVs, except Na-ion and solid-state BEVs, which do not rely on graphite. Constraints on Co increase the passenger travel of LFP and Na-ion BEVs, while Ni constraints similarly shift the mix toward LFP-based BEVs. Nd constraints substantially reduce passenger travel of both BEVs and FCEV because both rely on NdFeB magnets. Pt constraints almost exclusively affect FCEV, sharply reducing its passenger travel while simultaneously increasing that of BEV through substitution.

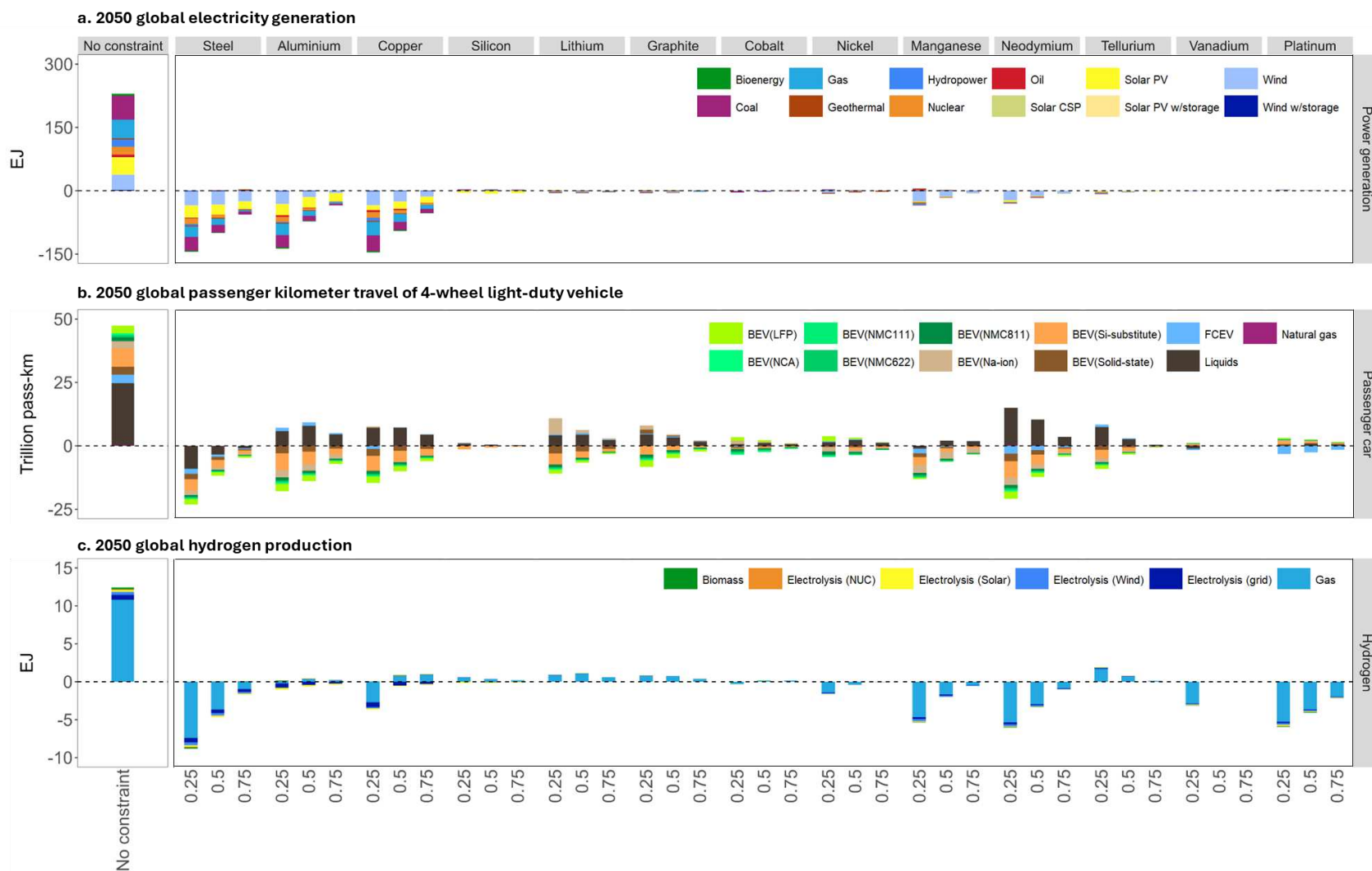


Figure 5. Global electricity generation (a), passenger kilometer travel of 4-wheel light-duty vehicle (b), and hydrogen production (c) in 2050 under the *Central scenario* (first bar plots on the right, showing absolute value), and their changes under the *Constraint scenarios* (other bars in the wide panel on the right).

The impacts of material constraints also propagate through multi-sector interactions. For instance, with bulk material constraints, the reduction in electricity generation raises electricity prices (**Figure 6**), which further weakens the cost competitiveness of BEVs by increasing their operating costs—reinforcing the direct effects of higher vehicle costs that shift passenger travel toward ICE vehicles under these scenarios. Similar multi-sector interaction is also shown between the transportation and hydrogen sectors. Under Nd and Pt constraints, reduced deployment of FCEVs in the transportation sector lowers hydrogen demand, which subsequently reduces hydrogen production. In contrast, constraints on Li and graphite limit BEV deployment and its service output, but these constraints increase FCEV deployment as a substitute, raising hydrogen demand and leading to higher hydrogen production (**Figure 5**). These cross-sector dynamics highlight that material constraints can reshape service output not only through direct impacts on technology deployment but also through broader system interactions that propagate across multiple sectors.

Impacts of production constraints on energy service prices

Materials that generate large declines in sectoral service output also drive substantial increases in energy service prices. For example, in the power sector, the 50% production constraints on bulk materials, such as steel, Al, and Cu, increase U.S. electricity prices in 2050 by 70%, 39%, and 59%, respectively (**Figure 6**). Other materials have comparatively minor impacts on electricity prices due to their more limited use in power-sector technologies and the availability of substitutes or alternative technology pathways. A similar pattern appears in the hydrogen production sector. Steel and Cu constraints at the 50% production level increase 2050 U.S. hydrogen production costs by 52% and 10%, respectively.

In the transportation sector, material constraints affect mobility service costs differently across drivetrain types. Constraints on bulk materials raise service costs for ICE vehicles, FCEVs, and BEVs

alike, as all drivetrains require steel, Al, and Cu. Mn and Nd constraints also increase costs across all drivetrains due to their use in steel alloys and electric motors (which use Mn and Nd, respectively). Other specialized materials generate drivetrain-specific cost effects. For example, a 50% Pt constraint raises 2050 FCEV costs in the U.S. by 23%, while constraints on Li-ion battery related materials (Li, graphite, Ni, Co) increase BEV costs by 10–15%. Across all sectors, tightening constraints from 50% to 25% of material supply availability leads to disproportionately larger cost increases compared to tightening from 75% to 50%, indicating a nonlinear relationship in which energy service prices escalate more rapidly as material constraints become more stringent.

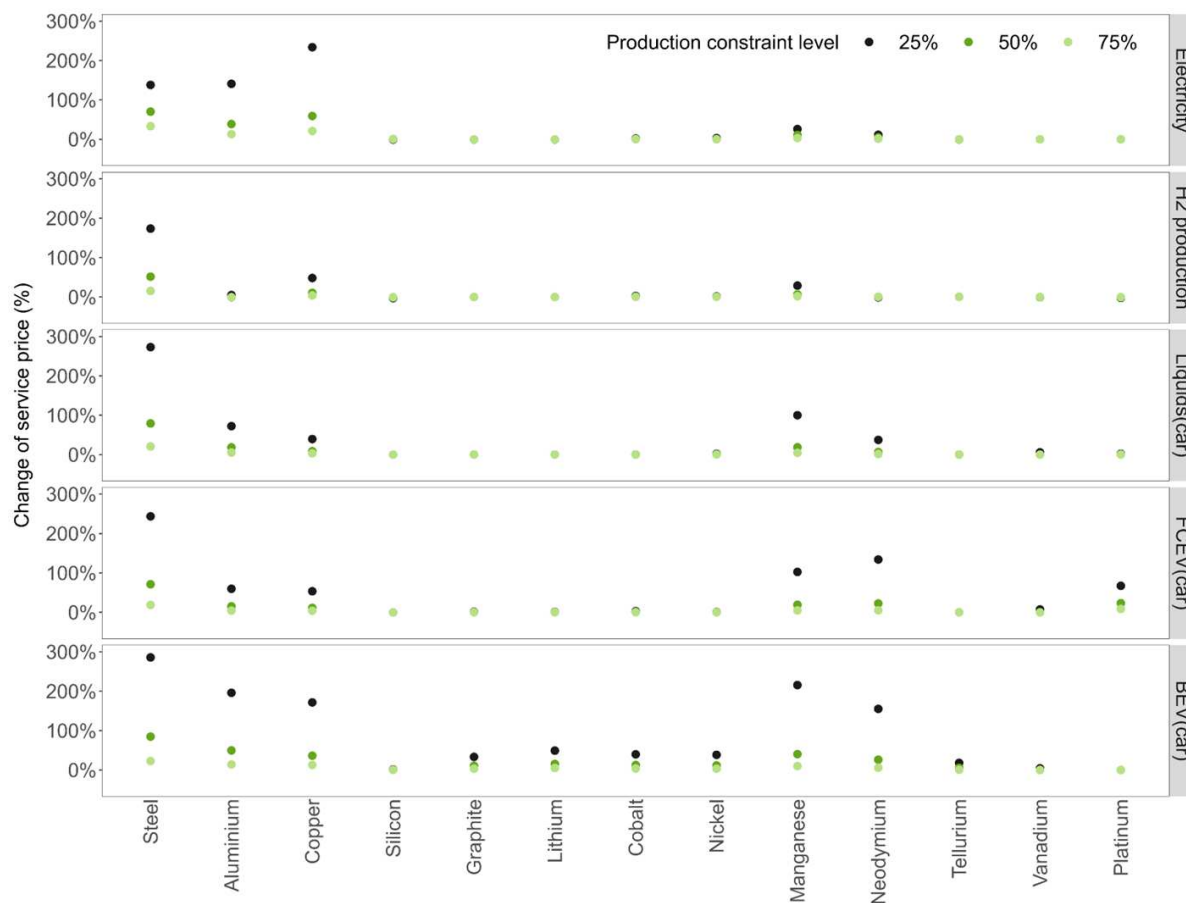


Figure 6. The impacts of material production constraint on 2050 energy service prices by sector/technologies (relative to the *Central scenario*). Results based on US 2050 service prices in different sectors.

Discussion

The energy system comprises a network of coupled interactions spanning primary energy production, energy transformation, and final end-use sectors²³. Our results demonstrate that cross-sector interdependency is a key mechanism through which CMM production constraints lead to system-wide impacts. These linkages cause changes originating in one sector to propagate throughout the system, altering technology deployment and shifting energy service outputs and prices. For example, constraints on bulk materials reduce electricity supply and raise electricity prices; these increases, combined with higher BEV non-energy costs under the same scenarios, diminish the cost competitiveness of BEV. By representing multiple sectors simultaneously, our analysis can capture this type of cross-sector dynamics and contribute to the growing literature on economy-wide implications of CMM production constraints.

Our findings also underscore the system-wide importance of bulk materials—steel, Al, and Cu. Because they are used across nearly all energy technologies and infrastructure systems, production constraints on these materials lead to large reductions in service outputs and price increases. Their pervasive role suggests that ensuring adequate supplies of bulk materials through both supply- and demand-side measures is essential for future energy system development^{24,25,17}. In contrast, specialty materials—such as Li, Co, Ni, rare earth elements, and platinum-group metals—are critical to specific technologies including Li-ion batteries, NdFeB-based wind turbines, and proton exchange membrane (PEM) fuel cells. For these materials, technology substitution—for example, Na-ion batteries²⁶, non-REE wind turbine designs²⁷, or low-Pt electrolysis systems²⁸—represents a key strategy for reducing vulnerability to supply risks^{29,30}.

This study further reveals nuances in technological vulnerability through the material–technology nexus, which characterizes the coupled relationship between material availability and technology

deployment. Two factors are important to this nexus. First, cross-sector linkages influence how cost or service output changes propagate across the energy system, shaping technology deployment. Second, technology-specific material intensity determines sensitivity to material price changes. Technologies with a higher cost share of a specific material experience sharper reductions in deployment when the material price increases under tightened supply conditions. By mapping technologies to the materials which they could be vulnerable to, our results provide useful insights to identify material-related vulnerabilities and could inform supply-chain or technological strategies to mitigate them.

Taken together, these findings demonstrate that understanding the implications of CMM supply availability requires a holistic systems perspective. The consequences of CMM production constraints are shaped not only by the direct material uses of individual technologies but also by the broader network of interactions that affect energy production, prices, and cross-sector demand patterns. By quantifying these interactions within an integrated, multi-sector modeling framework, this study offers insights into the mechanisms through which CMM constraints influence energy system development.

Future work

Future work could further strengthen and broaden this analysis. First, although this study covers on several key sectors of the economy such as the electricity, transportation, and hydrogen production sectors, many other parts of the economy—including industry, defense, and AI and data-center infrastructure—also depend on bulk and specialty materials^{1,2}. Incorporating these sectors would provide a more complete picture of economy-wide CMM competition and better capture the multi-sector effects.

A second direction for future research is to investigate additional factors that shape sectoral competition for CMM. This study highlights the role of sectoral linkages and technology-specific material intensities, but other forces could be also influential. For example, governmental or other institutional interventions could influence the economic competition of material allocation by prioritizing sectors deemed strategic—such as defense and critical infrastructure—through stockpiling³¹, targeted subsidies³², or direct allocation mechanisms^{33,34}. Trade strategies that restrict certain CMM end uses^{35,36} and firm-level procurement contracts or long-term CMM security agreements^{37,38} may also mediate CMM availability and alter technology deployment outcomes. Representing these institutional and geopolitical influences could strengthen understanding of how CMM supply availability interacts with broader economy.

Finally, evaluating CMM production constraints under alternative energy system pathways would enhance the robustness of insights. This study focuses on a business-as-usual pathway, but scenarios with high renewable penetration, accelerated electrification, or hydrogen-intensive strategies may impose different pressures on bulk and specialty materials. A broader set of scenarios would allow for a more comprehensive characterization of sensitivity to CMM production constraints across diverse plausible futures and enhance understanding of the conditions under which constraints on CMM availability become most acute.

Methods

Global Change Analysis Model (GCAM)

In this study, we use the Global Change Analysis Model (GCAM v7.2). GCAM v7.2 is an open-source, integrated, multi-sector model, which is available in a public repository³⁹. It represents the behavior and interactions among five systems: economy, energy, agriculture and land use, water, and climate⁴⁰. These systems have different geographical resolutions, including 32 energy-economy regions, 384 land subregions, and 235 water basins across the globe. GCAM v7.2 operates in 5-year time-steps from 2015 (model calibration year) to 2100 (in this study, the model solves until 2050), and is driven by exogenous assumptions about population growth, labor participation rates, and labor productivity in the 32 geopolitical regions, together with other assumptions of resources, technologies, and policy.

The operating principle of GCAM v7.2 is based on market equilibrium. It solves for equilibrium prices through iterative simulations to ensure that supplies match demands for various energy, agricultural, water, land-use, and GHG markets in each time-step and region⁴¹. Each system in GCAM v7.2 has technological detail. Individual technologies compete for market share based on their costs and choice parameters in a modified logit discrete choice model. In the model, technology share is determined by its levelized cost mediated by the influence of non-cost factors.

Representation of critical minerals or critical materials

The definition of “critical” minerals or materials is context-specific and reflects policy priorities, economic structure, and methodological choices, which vary across institutions and jurisdictions^{42–45}. Under the U.S. Department of Energy’s (DOE) official framework and the *Energy Act of 2020*⁴⁶, a critical mineral is defined as any mineral, element, substance, or material designated by the U.S.

Geological Survey, acting on behalf of the Secretary of the Interior, as essential to economic or national security and characterized by a supply chain vulnerable to disruption⁴⁷. A critical material, defined more specifically in the energy context, refers to any non-fuel mineral, element, substance, or material that the DOE determines both: a) has a high risk of supply chain disruption, and b) performs an essential function in one or more energy technologies, including those involved in producing, transmitting, storing, or conserving energy⁴⁵. These definitions emphasize the dual criteria of functional importance and supply risk.

In this study, we select 13 materials primarily from those identified as critical minerals or critical materials in the U.S. context. Our selection also identifies materials that are used across multiple technologies and sectors, enabling us to assess potential multi-sectoral linkages and evaluate how production constraints in one material may propagate through interconnected energy systems. Although steel is not designated as a critical mineral or material under the current U.S. definition, we include it due to its foundational role in energy infrastructure and the broader economy. Steel is a key structural material in power plants, renewable energy systems, hydrogen infrastructure, transportation systems, and industrial facilities. Given its large production volume and central role in energy technologies, understanding its future demand remains essential for evaluating material–energy interactions and potential resource pressures. Including steel therefore improves the completeness of the material demand representation, even though it is not classified as “critical” under policy definitions. It is worth noting that the material representation in GCAM is designed to be flexible, allowing additional materials to be incorporated as new research questions emerge or improved data become available. While this study focuses on 13 materials to demonstrate the modeling framework and its capability to capture material–energy system interactions, the structure readily accommodates expansion in future analyses.

Representation of sectors and technologies

This work builds on our previous efforts to expand material demand modeling in GCAM beyond the power generation sector to include multiple additional energy-system sectors¹⁹. Specifically, we extend material demand representation to the electricity transmission and distribution (T&D) system, transportation, and hydrogen production, enabling multi-sector coverage of material demand across energy systems in GCAM.

We applied a bottom-up approach to model material demand from multiple energy-system sectors by leveraging GCAM's detailed technology representations in each sector and technology material intensities. In our previous work, we enhanced the technological detail of the power generation sector by explicitly representing subtypes of solar photovoltaic (PV) systems, onshore and offshore wind turbines, and battery energy storage. In this study, we further expand technology detail in the transportation sector by representing different battery technologies in electric vehicles, including lithium iron phosphate (LFP), nickel cobalt aluminum (NCA), nickel manganese cobalt (NMC), sodium-ion, and solid-state batteries. A detailed description of technology representation in each sector is provided in **Supplementary Note 1**. Because different technology subtypes require different materials and use them at different intensities, this level of technological detail ensures more accurate estimates of material demand and allows technology substitution in response to constraints on material supply availability.

In the current model configuration, material demand is explicitly represented only for a subset of energy-related sectors (i.e. electricity, transportation, and hydrogen production). Other major energy transformation sectors in GCAM, such as oil refining and gas processing, are not included in the CMM demand accounting. As a result, when material production constraints are imposed, they directly affect only the sectors with explicit material representation, while the energy transformation

pathways not included in the CMM demand accounting remain unconstrained. This incomplete coverage could overstate the potential shift in energy generation away from electricity toward other transformation pathways (e.g., oil refining and gas processing) observed under bulk material constraint scenarios. This aspect of the current modeling framework could be further improved in future work by expanding material demand representation across a broader set of sectors.

Engineering estimates and order-of-magnitude calculations (see **Supplementary Note 4**) indicate that oil refining and gas processing systems have lower bulk material intensities (e.g., material use per unit of energy throughput) than electricity generation technologies, particularly renewables. Therefore, although the reallocation of energy supply away from electricity may be somewhat overstated due to incomplete material representation, the qualitative mechanism remains robust: material constraints disproportionately affect more material-intensive electricity technologies, leading to a reallocation of energy generation toward less material-intensive transformation pathways. The broader energy transformation system also exhibits greater flexibility in substitution compared with sectors such as transportation, where service substitution options are more limited.

Material intensity data and cost structure modification

Material intensity data for each technology are compiled from literature and used as model inputs. For those energy sectors in which material demand is represented, GCAM tracks technology vintages in each model period based on technology lifetimes and retirement assumptions, and estimates energy service outputs associated with new vintages in each period. Material demand is calculated by applying technology-specific material intensity coefficients—expressed as mass per unit of energy service output—to the service output of new technology vintages, yielding annualized material demand for each model period. The material intensity data used in this study are provided

in the **Supplementary Dataset**, and a detailed description of the data sources and necessary processing methods for GCAM implementation is presented in **Supplementary Note 2**.

We also modify the technology cost structure by separating material costs from overnight capital costs or non-energy technology costs. Material costs are calculated as the product of technology-specific material intensities and endogenous material prices, following the same approach developed in our previous studies¹⁹. This cost-structure modification enables material price changes to directly affect technology costs and competition within GCAM, allowing the model to capture the impacts of potential material production constraints on energy system transitions.

448 **Reference**

- 449 1. Bobba, S., Carrara, S., Huisman, J., Mathieux, F. & Pavel, C. Critical raw materials for strategic
450 technologies and sectors in the EU. A Foresight Study. (2020).
- 451 2. Carrara, S. et al. *Supply Chain Analysis and Material Demand Forecast in Strategic*
452 *Technologies and Sectors in the EU–A Foresight Study*. (2023).
- 453 3. Manalo, P. Discovery to production averages 15.7 years for 127 mines. *S&P Global Market*
454 *Intelligence*, [https://www.spglobal.com/marketintelligence/en/news-](https://www.spglobal.com/marketintelligence/en/news-insights/research/discovery-to-production-averages-15-7-years-for-127-mines)
455 *insights/research/discovery-to-production-averages-15-7-years-for-127-mines* (2023).
- 456 4. Manalo, P. Average lead time almost 18 years for mines started in 2020–23. *S&P Global Market*
457 *Intelligence*, Apr (2024).
- 458 5. Pitron, G. The geopolitics of the rare-metals race. *The Washington Quarterly* **45**, 135–150
459 (2022).
- 460 6. Leruth, L., Mazarei, A., Régibeau, P. & Renneboog, L. Green energy depends on critical
461 minerals. Who controls the supply chains? (2022).
- 462 7. Bebbington, A. J. et al. Resource extraction and infrastructure threaten forest cover and
463 community rights. *Proceedings of the National Academy of Sciences* **115**, 13164–13173 (2018).
- 464 8. Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V. & Tost, M. Surge in global metal mining
465 threatens vulnerable ecosystems. *Global Environmental Change* **69**, 102303 (2021).
- 466 9. Fikru, M. G. An economic framework for assessing the impact of domestic mining policies on
467 affordable energy transition. *Sci Rep* **14**, 13615 (2024).
- 468 10. Yao, B. et al. Understanding supply chain constraints for the US clean energy transition. *npj*
469 *Clean Energy* **1**, 9 (2025).
- 470 11. Watari, T. et al. Total material requirement for the global energy transition to 2050: A focus on
471 transport and electricity. *Resources, Conservation and Recycling* **148**, 91–103 (2019).

- 472 12. Wang, S. *et al.* Future demand for electricity generation materials under different climate
473 mitigation scenarios. *Joule* **7**, 309–332 (2023).
- 474 13. Calderon, J. L., Smith, N. M., Bazilian, M. D. & Holley, E. Critical mineral demand estimates for
475 low-carbon technologies: What do they tell us and how can they evolve? *Renewable and*
476 *Sustainable Energy Reviews* **189**, 113938 (2024).
- 477 14. IEA. *Global Critical Minerals Outlook 2025*. [https://www.iea.org/reports/global-critical-](https://www.iea.org/reports/global-critical-minerals-outlook-2025)
478 [minerals-outlook-2025](https://www.iea.org/reports/global-critical-minerals-outlook-2025) (2025).
- 479 15. Wang, H. *et al.* China’s electric vehicle and climate ambitions jeopardized by surging critical
480 material prices. *Nat Commun* **14**, 1246 (2023).
- 481 16. Yuan, P. *et al.* Material price surges threaten an equitable and timely renewable energy
482 transition. *One Earth* **0**, (2025).
- 483 17. Brown, M., Hotchkiss, E., Collins, G., Seyedrezaei, M. & Bazilian, M. No Minerals, No
484 Megawatts: How material costs and availability shape the future of the US power sector.
485 *Resources Policy* **106**, 105607 (2025).
- 486 18. Guo, J., Zhu, K. & Cheng, Y. Deployment of clean energy technologies towards carbon neutrality
487 under resource constraints. *Energy* **295**, 131012 (2024).
- 488 19. Qiu, Y. *et al.* The impacts of material supply availability on a transitioning electric power sector.
489 *Cell Reports Sustainability* **1**, (2024).
- 490 20. Shi, H. *et al.* Critical mineral constraints pressure energy transition and trade toward the Paris
491 Agreement climate goals. *Nat Commun* **16**, 4496 (2025).
- 492 21. Miller, H., Dikau, S., Svartzman, R. & Dees, S. The stumbling block in ‘the race of our lives’:
493 Transition-critical materials, financial risks and the ngfs climate scenarios. (2023).
- 494 22. Joint Global Change Research Institute. GCAM Documentation (Version 8.2). (2025).

- 495 23. Berjawi, A. E. H., Walker, S. L., Patsios, C. & Hosseini, S. H. R. An evaluation framework for
496 future integrated energy systems: A whole energy systems approach. *Renewable and*
497 *Sustainable Energy Reviews* **145**, 111163 (2021).
- 498 24. Helbig, C., Wietschel, L., Thorenz, A. & Tuma, A. How to evaluate raw material vulnerability - An
499 overview. *Resources Policy* **48**, 13–24 (2016).
- 500 25. Liang, Y., Kleijn, R., Tukker, A. & van der Voet, E. Material requirements for low-carbon energy
501 technologies: A quantitative review. *Renewable and Sustainable Energy Reviews* **161**, 112334
502 (2022).
- 503 26. Yao, A., Benson, S. M. & Chueh, W. C. Critically assessing sodium-ion technology roadmaps
504 and scenarios for techno-economic competitiveness against lithium-ion batteries. *Nat Energy*
505 **10**, 404–416 (2025).
- 506 27. Ozmen, T., Ergun, B. E., Gulbahce, M. O. & Onat, N. Rare-Earth Magnet Free Flux-Switching
507 Generator for Wind Turbines in Micro-Grids: A Review. *CES Transactions on Electrical Machines*
508 *and Systems* **8**, 295–309 (2024).
- 509 28. Li, Z., Ge, R., Su, J. & Chen, L. Recent Progress in Low Pt Content Electrocatalysts for Hydrogen
510 Evolution Reaction. *Advanced Materials Interfaces* **7**, 2000396 (2020).
- 511 29. Løvik, A. N., Hagelüken, C. & Wäger, P. Improving supply security of critical metals: Current
512 developments and research in the EU. *Sustainable Materials and Technologies* **15**, 9–18 (2018).
- 513 30. Lee, Y. & Dacass, T. Reducing the United States’ risks of dependency on China in the rare earth
514 market. *Resources policy* **77**, 102702 (2022).
- 515 31. Thomason, J. S. *et al. From National Defense Stockpile (NDS) to Strategic Materials Security*
516 *Program (SMSP): Evidence and Analytic Support. Volume 1.* (2010).
- 517 32. Baskaran, G. Seven Recommendations for the New Administration and Congress: Building US
518 Critical Minerals Security. *Centre for Strategic & International Studies (CSIS)* (2024).

- 519 33. Wang, Z. Interventionism, Decoupling, and Reshuffle: New Developments in Global Supply
520 Chain Management. *China Q of Int'l Strategic Stud* **08**, 1–19 (2022).
- 521 34. Nicastro, L. A. US Defense Industrial Base. (2023).
- 522 35. Köstner, D. & Nonn, M. The 2020 Chinese export control law: a new compliance nightmare on
523 the foreign trade law horizon? *China-EU Law J* **8**, 81–95 (2023).
- 524 36. Zhao, D. *Contemporary Export Control Law of China*. (Springer Nature, Singapore, 2024).
525 doi:10.1007/978-981-99-9825-8.
- 526 37. Zhang, J. & Dimitrakopoulos, R. Optimising a Mineral Supply Chain Under Uncertainty with
527 Long-Term Sales Contracts. in *Advances in Applied Strategic Mine Planning* (ed.
528 Dimitrakopoulos, R.) 787–800 (Springer International Publishing, Cham, 2018).
529 doi:10.1007/978-3-319-69320-0_45.
- 530 38. Mancheri, N. A. *et al.* Resilience in the tantalum supply chain. *Resources, Conservation and*
531 *Recycling* **129**, 56–69 (2018).
- 532 39. Bond-Lamberty, B., Patel, P., Lurz, J. & et, al. JGCRI/gcam-core: GCAM 6.0. Zenodo
533 <https://doi.org/10.5281/zenodo.8010145> (2022).
- 534 40. Calvin, K. *et al.* GCAM v5. 1: representing the linkages between energy, water, land, climate,
535 and economic systems. *Geoscientific Model Development* **12**, 677–698 (2019).
- 536 41. Clarke, J. F. & Edmonds, J. A. Modelling energy technologies in a competitive market. *Energy*
537 *Economics* **15**, 123–129 (1993).
- 538 42. Nassar, N. T. & Fortier, S. M. *Methodology and Technical Input for the 2021 Review and Revision*
539 *of the US Critical Minerals List*. (2021).
- 540 43. Government of Canada. *The Canadian Critical Minerals Strategy From Exploration to Recycling:*
541 *Powering the Green and Digital Economy for Canada and the World*. (2023).

542 44. Grohol, M. & Veeh, C. Study on the Critical Raw Materials for the EU 2023. *Final Report DG*
543 *GROW* (2023).

544 45. Bauer, D. J. et al. *2023 Critical Materials Strategy*. (2023).

545 46. U.S. Congress. *Energy Act of 2020*. 134 Stat. 1182.

546 47. Nassar, N. T. et al. *Methodology and Technical Input for the 2025 US List of Critical Minerals—*
547 *Assessing the Potential Effects of Mineral Commodity Supply Chain Disruptions on the US*
548 *Economy*. (2025).

549

550

551 **Funding sources**

552 This research was supported by the U.S. Department of Energy, Office of Science, as part of research
553 in MultiSector Dynamics, Earth, and Environmental System Modeling Program. The Pacific
554 Northwest National Laboratory is operated for DOE by Battelle Memorial Institute under Contract No.
555 DE-AC05-76RL01830. The views and opinions expressed in this paper are those of the authors alone.

556 **Author contributions**

557 Y.Q., B.Y., G.I., N.G., and M.W. designed the study. Y.Q., B.Y., G.I., N.G., and P.P. conducted the model
558 development. Y.Q., and B.Y., wrote the paper with inputs from all other co-authors.

559 **Competing interests**

560 The authors declare that they have no competing interests.

561

Figure 1. Global material demand across sectors under *Central scenario* (no constraint on material annual production)

Figure 2. Percentage change of material demand under *Constraint scenarios* at 50% level. Results calculated based on cumulative demand of each material (from electricity, transportation, and hydrogen production sectors) from 2025 to 2050. Each row represents a constrained scenario, where the row label indicates the material subject to the production constraint. Value > 0 implies an increase in demand relative to the *Central scenario*, while value < 0 implies a decrease in demand relative to the *Central scenario*. Note: the percentage change in the diagonal of the heat map is not exact 50% reduction. This is due to the constraint assumption we made. Under production constraint at 50% level, we assume that the 2025 value of the constraint (equal to 2025 demand in *Central scenario*) is linearly interpolated to 2050 which is equal to the 50% 2050 demand in the *Central scenario*. Therefore, under 50% material constraint level, the reduction of cumulative demand during 2025 and 2050 may not be exact 50%. A figure showing the estimated material demand projections under *Central scenario* and production constraint trajectories are showing in **SI-Figure 2**. The percentage change results of material demand for each sector (50% production constraint level) are showing in **SI-Figure 3-5**.

Figure 3. Changes in sectoral material demand under material production constraints. In each panel, the production constraints are applied to one material, and the dots represent the relative change (%) of sectoral material demand (under different production constraint levels) compared to the *Central scenario*. Results are calculated based on cumulative demand (from 2025 to 2050) for each sector.

Figure 4. Heatmap showing the impact of material production constraints (under 50% level) on new technology deployment (cumulative from 2025 to 2050) in different sectors. Each row represents one *Constrained scenario*, which applies annual production constraint at 50% level to one material. The column represents individual technology. Value > 0 implies increased new deployment under a material production constraint, while value < 0 implies decreased new deployment under a material production constraint. A detailed explanation on technologies represented in different sectors can be found in **Supplementary Note 1** and **SI-Table 1** to **SI-Table 3**.

Figure 5. Global electricity generation (a), passenger kilometer travel of 4-wheel light-duty vehicle (b), and hydrogen production (c) in 2050 under the *Central scenario* (first bar plots on the right, showing absolute value), and their changes under the *Constraint scenarios* (other bars in the wide panel on the right).

Figure 6. The impacts of material production constraint on 2050 energy service prices by sector/technologies (relative to the *Central scenario*). Results based on US 2050 service prices in different sectors.

Table 1. Scenario design in this study

	Constraints on material production
Central scenario	No constraint
Constrained scenarios	Exogenous production constraint on 13 materials at 3 levels (25%, 50%, 75%). We have a total of $13 \times 3 = 39$ <i>Constrained scenarios</i>. Each <i>Constrained scenario</i> limits the annual production of one material at one level. Under each level, the production constraint starts from 2025 to 2050. The 2025 value of the constraint is equal to the 2025 demand of the material from electricity, transportation, and hydrogen production sectors. The 2025 constraint value is linearly interpolated to the 2050 constraint value which is equal to the percentage of the 2050 annual material demand from the same three sectors in the <i>Central scenario</i>. (e.g., in the 25% case, annual production constraint of the material in 2050 is set to be 25% of the estimated annual 2050 demand in the <i>Central scenario</i>). Figures showing the annual production constraint trajectories in comparison to annual material demand projections in the <i>Central scenario</i> are provided in SI-Figure 2.

598

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [MultisectorCMMpaperSI.pdf](#)