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Material demand and supply-chain assessment of U.S. electricity system transitions

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Abstract

Decarbonizing the U.S. electricity sector will require rapid deployment of generation, storage, and transmission infrastructure, increasing demand for materials. We develop an integrated framework that quantifies annual and cumulative material demand from 2027 to 2050 across an ensemble of U.S. electricity futures spanning alternative policy, technology, and economic assumptions. Across the scenario ensemble, annual demand generally peaks during the late 2020s and 2030s before declining or moderating, with accelerated decarbonization increasing peak demand and more gradual decarbonization sustaining demand over longer periods. Demand uncertainty is driven primarily by U.S. electricity system scenarios for bulk commodities and base and alloying metals, and by material intensity assumptions for specialty metals and rare earth elements. We assess supply-chain vulnerabilities using metrics that characterize current supply-chain structure and compare projected material demand with current domestic and global production and reserves. Projected domestic material demand exceeds current domestic production and reserves for multiple materials, while remaining below current global supply for most. Tellurium, dysprosium, terbium, indium, and neodymium exhibit convergent but distinct supply-chain vulnerabilities, reflecting different combinations of elevated demand relative to global supply, high U.S. import reliance, and geographically concentrated primary production and processing. This framework, which integrates material demand projections with multidimensional supply-chain assessment, can be used to inform energy system planning, technological innovation, and public policy.

Introduction

Decarbonizing the electricity system is central to achieving economy-wide net-zero greenhouse gas emissions and limiting global warming [1–3], requiring unprecedented expansion of generation, storage, transmission, and associated supply chains [4,5]. In the United States, state and federal policy has increasingly shaped the pace and composition of electricity system transitions. The Inflation Reduction Act (IRA) of 2022 introduced tax incentives for clean electricity deployment, domestic manufacturing, and critical mineral supply chains, with the objective of accelerating decarbonization while strengthening U.S. industrial competitiveness and energy security [6]. Subsequent legislative and executive actions, including the One Big Beautiful Bill Act of 2025 [7,8] and associated implementation changes, have modified or accelerated the phase-out of several clean energy incentives, increasing uncertainty in future deployment trajectories [9].

Material availability has the potential to be a barrier and enabler of electricity system transitions and climate change mitigation [10,11] alongside financial, technological, social, and institutional factors [12]. Energy technologies require large volumes of bulk commodities, base and alloying metals, specialty metals, and rare earth elements, many of which are characterized by geographically concentrated production, high import dependence, and long supply-chain development horizons [13,14]. Understanding how alternative electricity-system pathways translate into future material demand – and whether domestic and global supply chains can support that demand – is therefore an increasingly important consideration for energy system planning, technological innovation, and public policy.

Prior studies have evaluated technology-specific material requirements and projected material demand associated with electricity-system pathways. Material requirements vary substantially across technologies [14–23]. Decarbonization can increase the magnitude and alter the composition of material demand, with variation across electricity-system pathways driven by technology choice, policy, and material-intensity assumptions [10,11,17,24]. U.S.-focused assessments of renewable technology pathways have found that deep decarbonization could increase requirements for several specialty metals and rare earth elements, in some cases to levels large relative to current global production [13,25]. More recent work has incorporated material prices and availability, demonstrating that supply constraints can alter technology deployment, system costs, and emissions [26]. Supply-chain assessments provide a complementary perspective by using indicators such as net import reliance and geographic supply concentration to identify potential sources of supply vulnerability [13,14,27]. However, limited work has connected projections of material demand with the structure and vulnerability of domestic and global supply chains.

This study develops an integrated framework to evaluate material demand induced by U.S. electricity-system decarbonization and supply-chain vulnerabilities. We combine an ensemble of 61 electricity-system scenarios spanning alternative assumptions regarding technology costs, fuel prices, electricity demand growth, policy, and climate targets with probabilistic material intensity distributions for 27 bulk commodities, base and alloying metals, specialty metals, and rare earth elements. We assess material supply chains using metrics characterizing current supply-chain structure (e.g., net import reliance, geographic concentration of supply, trade shares, country risk classifications) and comparing projected material demand to current domestic and global production and reserves.

Methods

The following sections detail the approach used to quantify material demand and assess supply-chain metrics and vulnerabilities associated with projected U.S. electricity-sector transitions.

Electricity supply projections

We use electricity capacity projections from the 2024 National Renewable Energy Laboratory (NREL) Standard Scenarios [28], generated using the Regional Energy Deployment System (ReEDS), a least-cost capacity-expansion and economic dispatch model of the contiguous U.S. electricity system [29]. The ensemble includes 61 scenarios varying technology cost, policy, and demand growth assumptions (Table S1). We simulate material demand across the full ensemble and focus on four representative scenarios: a reference case with the IRA (*Baseline with IRA*), a reference case without the IRA (*Baseline without IRA*), accelerated decarbonization achieving a 100% net reduction in electricity-sector carbon dioxide equivalent emissions relative to 2005 by 2035 (*Net-Zero by 2035*), and more gradual decarbonization achieving a 95% net reduction by 2050 (*Net-Zero by 2050*). Capacity projections are reported at three-year increments from 2026 to 2050 for 23 generation and storage technologies (Table S2); material demand is quantified for the 18 technologies with sufficient material intensity data, excluding technologies such as battery storage.

Annual capacity is estimated from the three-year projections using a piecewise cubic Hermite interpolation [30], which preserves monotonicity and shape while exactly reproducing each reporting-year value. This approach provides a smooth annualized capacity trajectory and does not reflect abrupt deployment changes arising from policy shifts, market conditions, or supply-chain constraints between reporting years. Annual capacity additions are calculated from consecutive annual capacities and represent gross primary additions. No capacity installed during the simulation horizon is assumed to retire, given all modeled technologies have expected operational lifetimes exceeding 25 years [31].

Material intensities

We use material-intensity estimates (metric tons per megawatt) from Liang et al (2022) for renewable technologies and Wang et al. (2023) for thermal technologies, yielding 1,326 observations across 169 technology-material pairs spanning 31 materials and four material classes (Table S3). Material intensities represent direct construction requirements and exclude upstream and end-of-life requirements.

Given that published estimates exhibit substantial variability arising from technology differentiation, construction practices, technological evolution, and life-cycle assessment methodology, material intensities are modeled as random variables. We assume a lognormal distribution form, which is appropriate for strictly positive quantities that commonly exhibit right-skewed variability [33]. Observation counts range from 1 to 102 per technology-material pair (median n = 3, mean n = 7.8), requiring different parameterization approaches depending on data availability (Table S4). For pairs with sufficient data ($n \geq 5$), distribution parameters are estimated by maximum likelihood and goodness-of-fit evaluated using Kolmogorov-Smirnov and Anderson-Darling statistics. For pairs with sparse data ($n < 5$), distributions are centered on the observed median intensity, while variability is represented using an analogue estimate derived from the median coefficient of variation (CV = 0.78, corresponding to $\sigma = 0.69$) observed across pairs with sufficient data ($n \geq 5$).

Technology categories are mapped between NREL Standard Scenarios and the material-intensity data (Table S2). Utility-scale photovoltaics are represented as a weighted mixture of crystalline silicon (79%) and cadmium telluride (21%) based on 2024 U.S. market shares (Seel et al. 2025).

Material demand simulation

Combining annual capacity additions with material intensities, we estimate annual material demand for each material, technology, and scenario. Material-intensity uncertainty is propagated using Monte Carlo simulation, with sampling continued for up to 10,000 iterations until the running mean stabilizes within a 1% relative tolerance. The framework captures uncertainty in reported material intensities but not in deployment trajectories, future technology design, substitution, or correlations among material intensities, which are assumed independent.

Supply-chain assessment

We characterize material supply chains using metrics grouped into two categories: (i) metrics describing the current supply-chain structure independent of material demand projections, and

(ii) metrics that compare projected material demand to current domestic and global production and reserves. The following sections describe the supply-chain metrics; material-specific deviations from the metrics described are summarized in Table S5.

Demand-independent metrics include net import reliance (NIR), geographic concentration of supply, supply shares by country, and country risk. NIR measures the percentage of U.S. apparent consumption supplied by net imports, where apparent consumption is defined as domestic production plus imports minus exports, adjusted for changes in stocks. We use NIR estimates from the United States Geological Survey (USGS) Mineral Commodity Summaries [35], averaged over 2020–2024, with years of net exports assigned a value of zero. The geographic concentration of supply is quantified using the Herfindahl–Hirschman Index (HHI), calculated as the sum of squared country shares of global primary production or processing, with higher values indicating greater concentration among a small number of countries. HHI is estimated using reported country production shares from the USGS Mineral Commodity Summaries, supplemented by processing-stage shares from the 2023 EU critical raw materials study where USGS does not report country-level data [35,36]. For rare earth elements, the HHI is estimated using reported processing shares because refining, rather than mining, represents the primary supply bottleneck [36,37]. We also quantify production shares (the shares of U.S. consumption supplied by each country, with the U.S. share given by one minus NIR and the imported share apportioned across partner countries) and reserve shares (the shares of the global reserve base held by the U.S. and its import partners, with partner countries identified from trade data and reserve quantities from the USGS Mineral Commodity Summaries), with trade data averaged over 2020–2023 [35,38]. Global production and reserve shares by country are obtained from the USGS Mineral Commodity Summaries [35].

We further overlay country risk classifications from the Organisation for Economic Co-operation and Development (OECD) [39] as an indicator of exposure to country-level economic and political risk among major suppliers. For the purpose of this study and to aid interpretation, we group countries into the following classes: U.S., China, *low risk*, *moderate risk*, *high risk*, and *not classified*. *Low-risk* countries include OECD classifications 1–3 and high-income OECD or euro-area countries without an OECD country risk classification; *moderate-risk* and *high-risk* countries correspond to OECD classifications 4–5 and 6–7, respectively; and countries without an applicable OECD classification, or for which country-specific production or reserves are not reported, are grouped as *not classified*.

In addition, we estimate the following four metrics comparing projected material demand to current domestic and global supply: (i) peak annual demand relative to U.S. production, (ii) peak annual demand relative to global production, (iii) cumulative demand over 2027–2050 relative to U.S. economically recoverable reserves, and (iv) cumulative demand relative to global economically recoverable reserves. Given that production represents an annual flow and reserves represent a stock, peak annual demand is compared with production while cumulative demand is compared with reserves. Production and reserve values are held fixed at their most recently reported levels [35]; consequently, these metrics evaluate projected demand against the current supply base and do not account for future mine development, processing capacity expansion, technological change, recycling, substitution, or reserve growth through new discoveries. Values greater than one indicate that projected demand exceeds current production or reserve levels.

Electricity capacity projections

Figure 1 depicts annual electricity capacity additions from 2027 to 2050 across the scenario ensemble. End-use electricity demand increases by approximately 25–45% by 2035 and 40–100% by 2050 relative to 2026, driving sustained investment in new generation. Renewable deployment exhibits the greatest variation, with cumulative solar and wind additions differing by more than a factor of two across scenarios by 2050, while coal is nearly eliminated in all scenarios. Natural gas follows divergent pathways: scenarios without binding net-zero targets expand unabated combined-cycle capacity, whereas deep decarbonization scenarios increasingly deploy gas with carbon capture and storage (CCS) and other firm low-carbon resources. Consequently, net lifecycle power-sector emissions span nearly three orders of magnitude by 2050, from approximately 1 Gt $CO_2e\ yr^{-1}$ in the highest-emitting scenarios to near zero in the most aggressive decarbonization scenarios. To capture this range while maintaining a tractable set of material-demand projections, this study focuses on four representative scenarios – *Baseline with IRA*, *Baseline without IRA*, *Net-Zero by 2035*, and *Net-Zero by 2050* – that capture differences in federal policy and climate targets. The IRA accelerates renewable deployment, while the net-zero pathways require earlier and more sustained infrastructure expansion, faster coal retirements, and greater deployment of firm low-carbon resources.

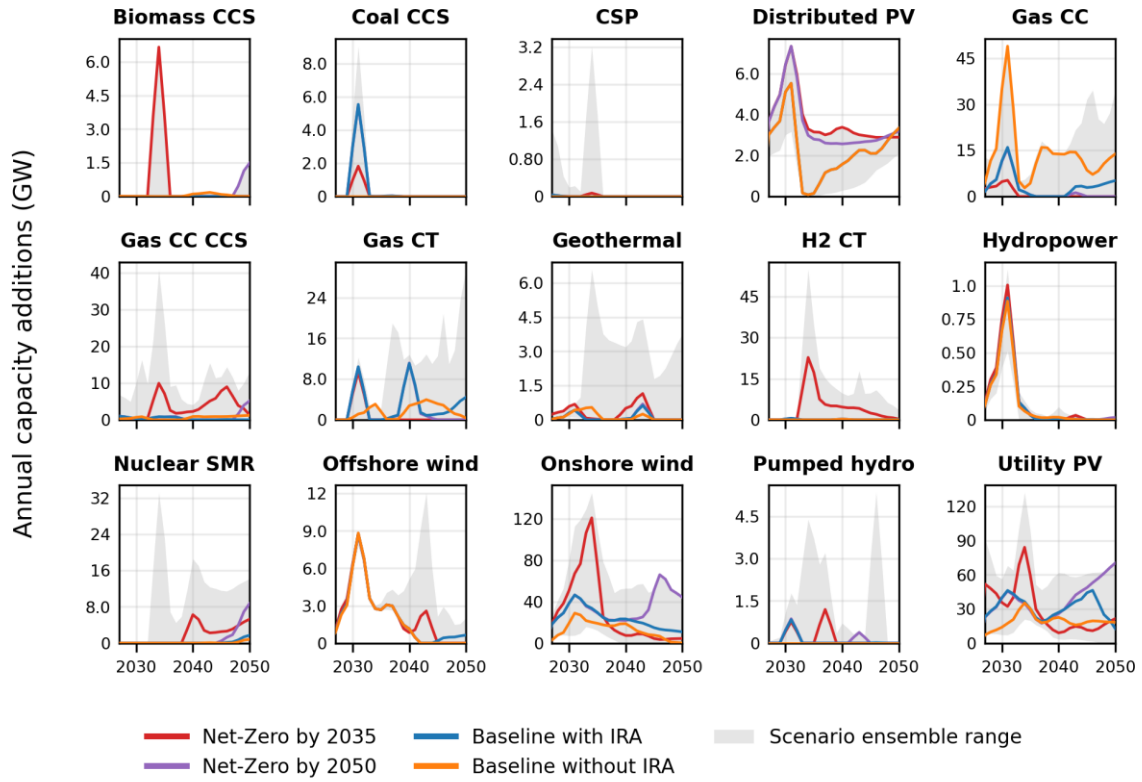

Figure 1. Annual capacity additions by energy technology from 2027 to 2050. Technology abbreviations are provided in Table S2. Coal without CCS, nuclear (except SMRs), and biomass without CCS are omitted because there are no capacity additions across the scenario ensemble.

Material demand projections

Figure 2 shows annual material demand from 2027 to 2050. Across the scenario ensemble, material demand generally peaks during the late 2020s and early 2030s, followed by lower but sustained demand through the 2040s. The *Baseline without IRA* scenario produces the lowest peak and cumulative demand, while the *Net-Zero by 2035* scenario produces the highest annual demand for most materials, with peak demand for many materials shifting into the mid-2030s as construction accelerates. The *Net-Zero by 2050* scenario closely follows the *Baseline with IRA* through the late 2030s before sustaining higher demand in the 2040s. Bulk commodities and most base and alloying metals broadly follow overall infrastructure deployment, while specialty metals and rare earth elements more closely reflect technology choice. Demand for cadmium, tellurium, and indium tracks with CdTe photovoltaic deployment and peaks later than most materials, whereas demand for silver and silicon demand tracks with photovoltaic deployment [40,41]. Alloying metals used in high-strength steels are most sensitive to wind deployment, and rare earth elements closely mirror permanent-magnet wind deployment [15,18]. These temporal patterns are generally consistent with previous global assessments of material demand [10,11,17,24].

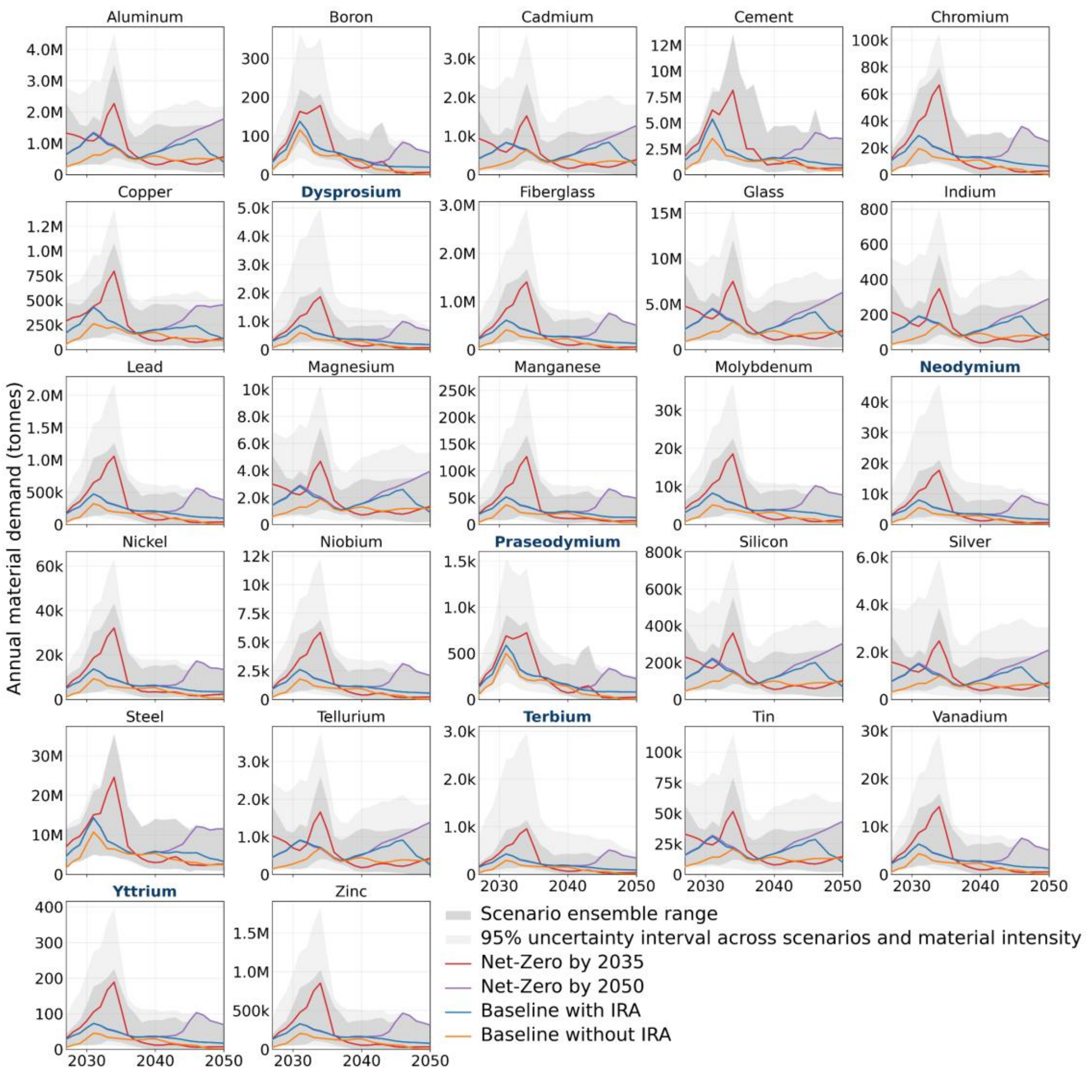

Figure 2. Annual material demand from 2027 to 2050. Colored lines indicate the mean demand for each of the four representative scenarios, dark gray bands indicate the range of the mean demand across the 61-scenario ensemble, and light gray bands indicate the 95% uncertainty interval, calculated from the pooled distribution of Monte Carlo iterations across scenarios. Table S7 includes peak mean annual demand for the representative scenarios.

Figure 3 presents mean cumulative material demand from 2027 to 2050 by material class across the four representative scenarios. The *Baseline without IRA* scenario consistently produces the lowest cumulative demand across all material classes because of slower renewable deployment, while the *Net-Zero by 2050* scenario results in the highest cumulative demand because deployment is sustained through the 2040s and achieves a larger total renewable build-out (Figure 1). Relative to the *Baseline with IRA* scenario, cumulative demand under the *Net-Zero by 2035* scenario increases for bulk commodities (+14%), base and alloying metals (+24%), and rare earth elements (+24%), while declining modestly for specialty metals (−5%); in comparison, the *Net-Zero by 2050* scenario exhibits larger increases across all material classes, including bulk commodities (+30%), base and alloying metals (+44%), specialty metals (+24%), and rare earth elements (+42%). Across all scenarios, bulk commodities dominate cumulative demand by mass, followed by base and alloying metals, while specialty metals and rare earth elements represent smaller but strategically important flows concentrated in photovoltaic and permanent-magnet wind technologies.

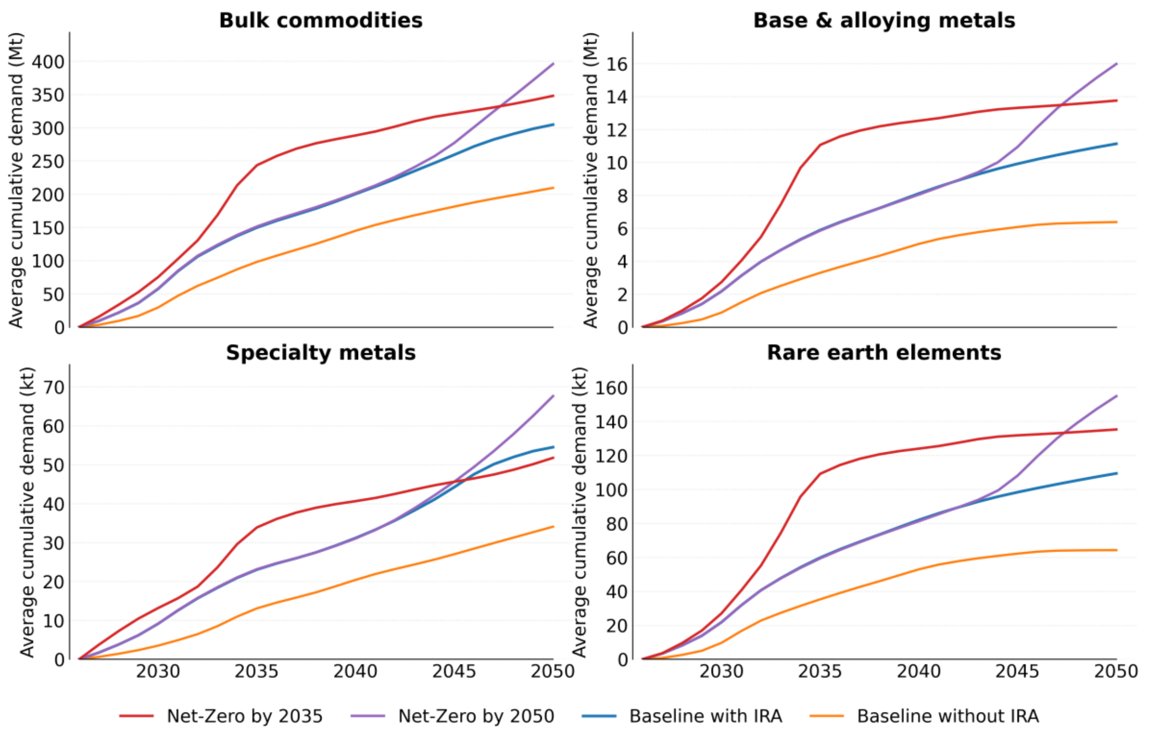

Figure 3. Mean cumulative material demand from 2027 to 2050 by material class. Values represent the mean across Monte Carlo simulation iterations. Table S8 includes mean cumulative demand by material for the *Baseline with IRA* scenario.

Modeled material demand reflects uncertainty in electricity-system scenarios and technology-specific material intensities (Figures 2, S2,and S3). Scenario variability dominates for bulk commodities and base and alloying metals because their use spans many technologies. In contrast, demand for specialty metals and rare earth elements is more sensitive to material-intensity uncertainty because their use is concentrated in a small number of technologies. This uncertainty primarily reflects variability among published material intensity estimates rather than limited data availability [18]. Reducing uncertainty entails improved scenario characterization for bulk commodities and base and alloying metals, and more detailed, standardized, technology-specific intensity data, such as distinguishing direct-drive from geared wind turbines or sintered from bonded permanent magnets, for specialty metals and rare earth elements. Time-varying material intensities also represent an important direction for future work as technologies evolve through learning, manufacturing innovation, and design optimization.

Supply-chain assessment of future material demand

Figure 4 compares projected material demand with current domestic production and reserves, in addition to the distribution of production and reserves among U.S. trading partners (Table S9). These metrics are used to assess domestic supply vulnerabilities. Under the *Baseline with*

IRA scenario, the mean peak annual demand from 2027-2050 exceeds current domestic production for ten materials (i.e., tellurium, dysprosium, terbium, cadmium, tin, lead, neodymium, aluminum, zinc, vanadium), while there is no domestic production of indium, manganese, niobium, and yttrium. Mean cumulative demand from 2027-2050 exceeds current domestic economically recoverable reserves of aluminum, tellurium, vanadium, and lead. Domestic supply vulnerabilities are limited for most bulk commodities such as steel and cement, which have established domestic production and comparatively diversified supply chains. Aluminum is the exception, with projected demand exceeding current domestic production and reserves despite established domestic production base. Several base and alloying metals (i.e., chromium, manganese, nickel, niobium, tin, vanadium) also exhibit domestic supply vulnerabilities arising from limited domestic supply and/or reliance on imports. Specialty metals (i.e., indium, tellurium, silver) and rare earth elements (i.e., neodymium, dysprosium, praseodymium, terbium, yttrium) exhibit both high import reliance and geographically concentrated foreign supply. Approximately 95% of rare earth elements are imported, more than half sourced from China, which also dominates the reserve base accessible through current U.S. trade relationships. Most other imported materials are sourced from countries classified as low risk, except chromium and niobium, for which more than half of imports originate from countries classified as moderate or high risk. These domestic supply vulnerabilities represent current supply-chain conditions rather than fixed future constraints, given that production capacity, economically recoverable reserves, and trade relationships can evolve with exploration, technological change, market development, and policy.

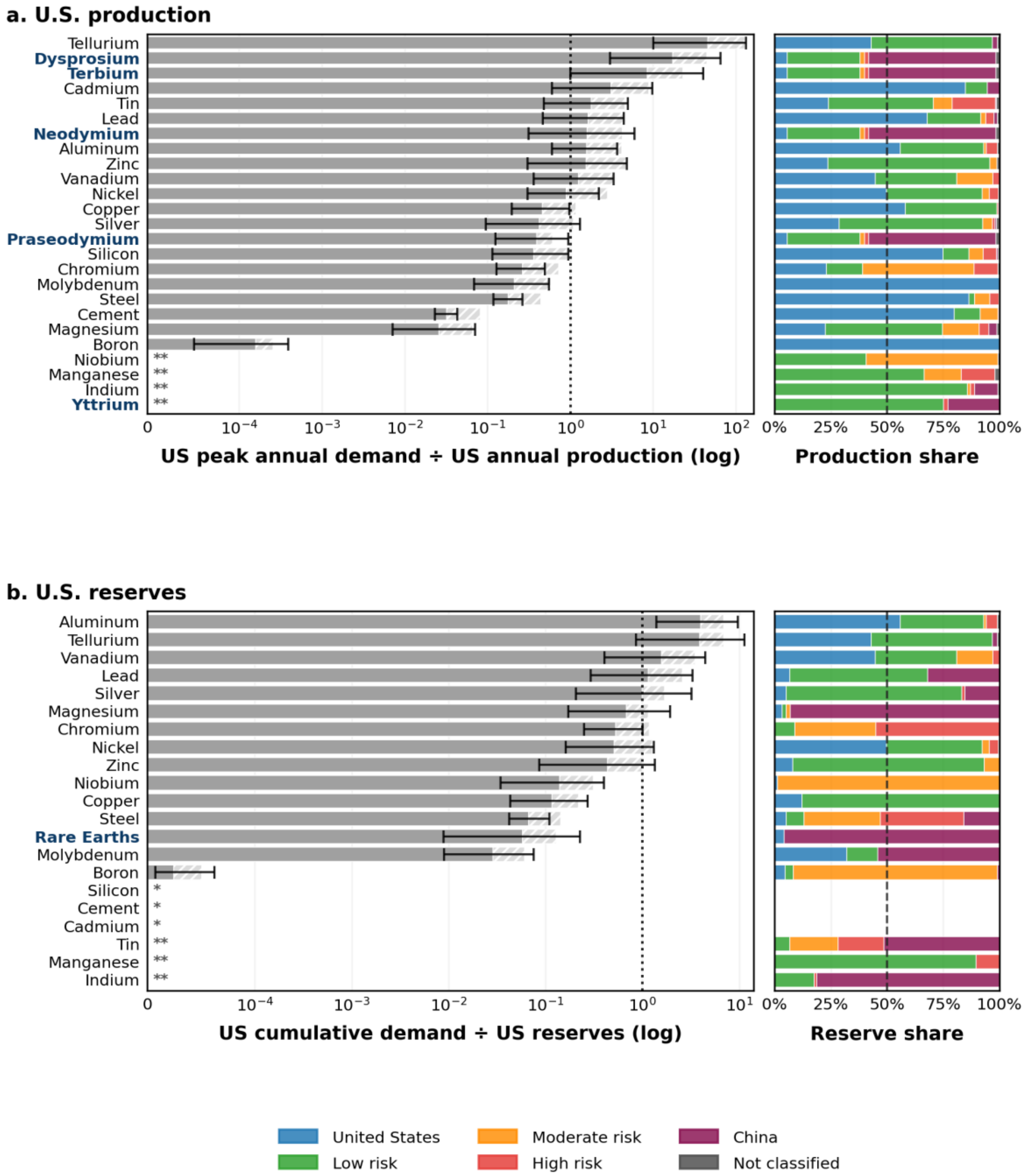

Figure 4. Comparison of projected material demand with current U.S. supply. (a) Projected peak annual demand from 2027-2050 relative to annual production, and the share of domestic consumption supplied by U.S. trading partner countries, categorized by country or risk class. (b) Projected cumulative demand from 2027-2050 relative to U.S. reserves, and the share of the global reserve base accessible through current U.S. trade relationships, categorized by country or risk class. In the supply-demand comparison bar charts, solid gray bars and error bars depict the mean and 95% confidence intervals, respectively, across Monte Carlo simulation iterations under the *Baseline with IRA* scenario; hatched gray bars depict the highest mean demand across the scenario ensemble; and dotted lines indicate thresholds over which domestic demand exceeds domestic supply. One asterisk indicates materials without a defined reserve concept, and two asterisks indicate materials with no reported U.S. production or reserves.

Figure 5 compares projected domestic material demand with current global production and reserves, in addition to the distribution of global production and reserves among all countries (Table S9). These metrics are used to assess global supply vulnerabilities. Projected domestic demand remains modest relative to global supply for most materials. Under the *Baseline with IRA* scenario, mean peak annual demand does not exceed current global annual production for any material. Domestic tellurium demand approaches current global production levels, consistent with previous work [10]. Under the highest-demand scenarios across the scenario ensemble, mean peak annual demand exceeds current global production for tellurium, dysprosium, and terbium, whereas indium is the only material for which mean cumulative demand exceeds reported global reserves. Global production is concentrated in China for most materials assessed, whereas global reserves are more geographically distributed, with concentration in China limited primarily to indium, magnesium, and rare earth elements. This global supply-chain vulnerability assessment assumes static supply. Moreover, these comparisons consider only demand associated with the U.S. electricity system and exclude concurrent demand from global energy transitions and competing end uses such as electrified transport, electronics, and defense.

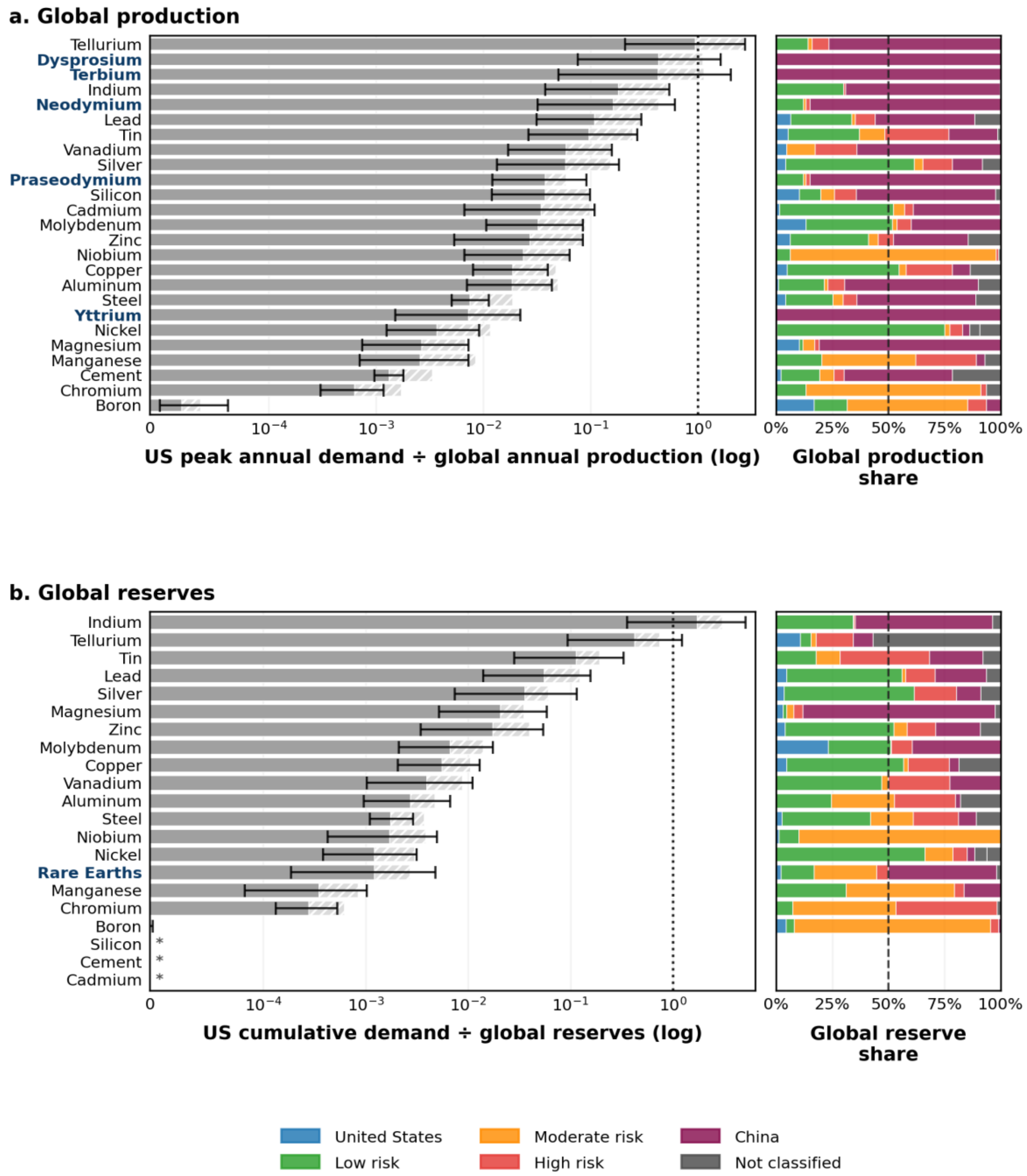

Figure 5. Comparison of projected material demand with current global supply. (a) Projected peak annual demand from 2027-2050 relative to annual global production, and the share of current global production by country or risk class. (b) Projected cumulative demand from 2027-2050 relative to global reserves, and the share of current global reserves by country or risk class. In the supply-demand comparison bar charts, solid gray bars and error bars depict the mean and 95% confidence intervals, respectively, across Monte Carlo simulation iterations under the *Baseline with IRA* scenario; hatched gray bars depict the highest mean demand across the scenario ensemble; dotted lines indicate thresholds over which projected U.S. demand exceeds current global production or reserves; and asterisks indicate materials without a defined reserve concept.

Figure 6 integrates demand stress (projected peak annual demand relative to current global production), U.S. net import reliance (NIR), and global production concentration quantified using the Herfindahl–Hirschman Index (HHI) to identify materials with converging supply-chain vulnerabilities. Bulk commodities and most base and alloying metals exhibit relatively low demand stress despite large absolute demand because global production is extensive and geographically diversified. In contrast, tellurium exhibits the highest demand stress, with projected annual demand approaching 95% of current global production under the *Baseline with IRA* scenario, while also exhibiting moderate NIR and HHI; this vulnerability reflects the combination of high projected demand from CdTe utility-scale photovoltaics [40,41] and supply constraints associated with its recovery primarily as a byproduct of copper refining [35]. Rare earth elements exhibit high NIR and HHI associated with the concentration of mining, separation, and magnet manufacturing in China [37], while dysprosium and terbium additionally exhibit high demand stress. Indium, which is a byproduct of zinc production, also has a high HHI and is entirely supplied through imports, and is the only material for which projected cumulative domestic demand exceeds reported global reserves [35]. These differing sources of supply-chain vulnerability may require distinct responses. Recycling, material and technology substitution, and expanded primary or byproduct recovery can reduce vulnerabilities at both domestic and global scales, whereas diversification of trading partners and strategic stockpiling primarily address domestic import dependence, and global supply constraints additionally require expansion and geographic diversification of primary production and processing capacity [39,41–43].

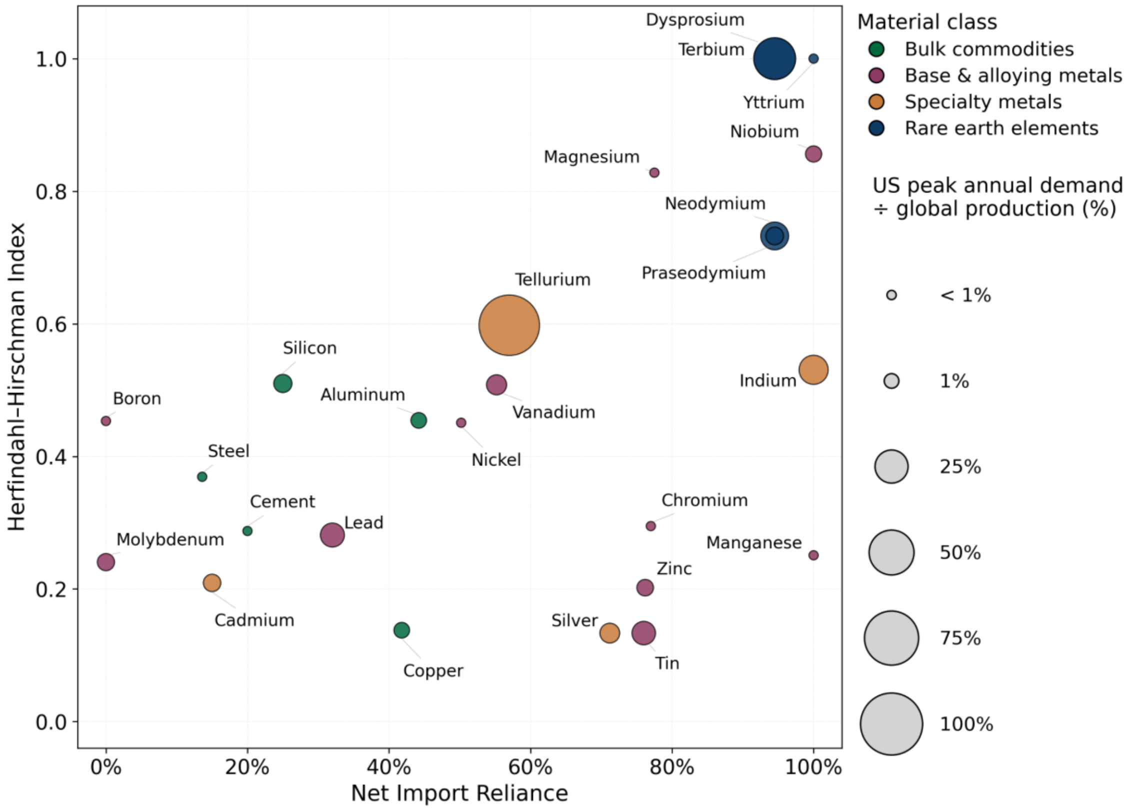

Figure 6. Supply-chain metrics by material and material class. Net import reliance (NIR) measures the percentage of U.S. apparent consumption supplied by net imports. The geographic supply concentration is quantified using the Herfindahl–Hirschman Index (HHI), calculated as the sum of squared country shares of global primary production or processing. The size of the markers is the projected peak annual demand from 2027-2050, averaged across the Monte Carlo simulation iterations, for the *Baseline with IRA* scenario divided by global production.

Conclusions

This study develops an integrated framework to evaluate material demand and supply-chain vulnerabilities associated with U.S. electricity-system transitions. Material requirements depend on the scale, timing, and composition of technology deployment. Accelerated decarbonization generally increases near-term demand and peak annual demand, whereas more gradual pathways sustain deployment over longer periods and increase cumulative material demand. Uncertainty is driven primarily by electricity-system scenario variation for bulk commodities and base and alloying metals, and by technology-specific material intensities for specialty metals and rare earth elements, implying different priorities for reducing uncertainty across material classes.

The supply-chain assessment highlights domestic and global supply vulnerabilities. Projected U.S. electricity-sector demand exceeds current domestic production and reserves for multiple materials, while remaining below current global supply for most. For several materials, vulnerabilities arise where elevated domestic demand coincides with high import reliance and concentrated production. Tellurium, dysprosium, terbium, indium, and neodymium exhibit particularly high vulnerability through different combinations of demand stress, import dependence, and concentrated primary production and processing.

These findings have implications for infrastructure planning, technological innovation, and public policy. For planning, material demand is an additional important consideration alongside objectives such as costs, reliability, and emissions when evaluating alternative electricity-system pathways. Planning frameworks that account for supply-chain vulnerabilities can help identify where rapid deployment may place pressure on domestic production, processing capacity, or import-dependent supply chains. For innovation, the results identify materials and technologies for which material efficiency, substitution, recycling, improved recovery, and alternative device designs have the potential to reduce future material demand or supply vulnerabilities. For policy, the multidimensional nature of supply-chain vulnerability points to different policy levers. For example, domestic import dependence may be addressed by measures such as diversification of trading partners, expanded domestic production, and strategic stockpiling, whereas high global production concentration or demand stress may be mitigated by the expansion and geographic diversification of primary production, processing, and recovery capacity.

Our results motivate several directions for future research. First, the scope of modeled energy-system pathways, and the associated material demand and supply-chain vulnerability, can be expanded. Emerging drivers of electricity-system transformation, such as digitization and data-center load growth, can be incorporated, in addition to demand and supply-chain vulnerabilities arising across multiple sectors and at global scales. Second, material supply and demand can be represented more dynamically. Future modeling can represent changes in material demand through evolving material intensities, substitution, recycling, and technology design, as well as changes in material supply through material production and processing capacity, reserves, and trade. Supply-chain vulnerability metrics can likewise be extended to reflect changes in both demand and supply over time. Third, material constraints and potential interventions can be integrated more directly into energy-system modeling to evaluate how material availability affects technology deployment, system costs, and transition pathways [26], while also examining how interventions alter those outcomes. Fourth, value-of-information analyses can be used to identify where improved material-intensity, processing, trade, or reserve data would provide the greatest reduction in decision-relevant uncertainty. Finally, the value of technological innovation and basic research can be assessed by identifying specific materials and technologies for which advances in material efficiency, substitution, alternative chemistries and designs, recycling, or recovery have the potential to reshape future material demand, technology deployment, and supply-chain vulnerability.

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Author contributions

Paul Griffths: methodology, software, formal analysis, writing – original draft, visualization. **Avery Moorhead:** software, formal analysis, writing – review & editing. **Maarten Brinkerink:** methodology, software, formal analysis, writing – review & editing, visualization. **Erin Mayfield:** conceptualization, methodology, formal analysis, writing – original draft, visualization, supervision.

Data and code availability

The data and code that support the findings of this study will be made openly available in a Zenodo repository upon publication. The repository will include data and code necessary to reproduce the results presented in this paper.

Conflict of interest statement

The authors declare no conflicts of interest.

Generative AI use

During the preparation of this manuscript, generative artificial intelligence (AI) tools were used as programming and writing assistants. Specifically, Anthropic's Claude Opus (versions 4.5–5) and Fable 5 supported code debugging and organization, visualization refinement, and copy-editing of author-written text. OpenAI's ChatGPT (GPT-5.5) supported copy-editing of author-written text. All research questions, study design, methodological decisions, analyses, interpretations, and conclusions were developed and verified by the authors.

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