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Christian Bogmans, Francis Cuadros-Bloch, Jean-Marc Natal, Andrea Paloschi

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ABSTRACT: Recent supply shortages have intensified concerns about supply chain bottlenecks, prompting policymakers to adopt industrial policies to promote reshoring and import diversification.
Rare earth element (REE) markets, where supply chains are highly concentrated across stages, particularly for refining, is a clear example. This paper quantifies the costs of de-risking supply chains using a dynamic global trade model calibrated with detailed market, industry andgeological data. In the model, upstream (mining) and downstream (refining) production is slow-moving and determined by investment in capacity (CAPEX). To illustrate the model's properties, we evaluate how different policies can decrease downstream REE exposure from any single supplier by comparing CAPEX subsidies and stylized revenue-support policies under unilateral and simultaneous action among various importers. De-risking supply chains through targeted industrial policies is fiscally costly, although less so if pursued simultaneously by various importers. The fiscal cost of downstream unilateral CAPEX subsidies, for example, drops from 134% of the annual U.S. REE market (about 1.13 billion dollars) by 2035, to 90% under simultaneous action by other REE importers. Of course, de-escalation of trade tensions remains the first-best outcome.

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Author's E-Mail Address:	cbogmans@imf.org; fcuadrosbloch@imf.org; jnatal@imf.org; apaloschi@imf.org.

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Industrial Policy and Supply Chain Bottlenecks in Commodity Markets: Evidence from Rare Earth Elements

Prepared by Christian Bogmans, Francis Cuadros-Bloch, Jean-Marc Natal, Andrea Paloschi.[1]

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1 Introduction

Interdependencies created by decades of globalization and the explosive growth of cross-border supply chains have become increasingly weaponized. Over the last decade, countries have progressively resorted to tariffs, sanctions, export controls, and other economic tools to pursue geopolitical objectives, most recently in the form of Western restrictions on semiconductors and Chinese restrictions on critical minerals (Dürr and Heilmann, 2025). As a result, global supply chains — long shaped exclusively by cost optimization — now face potential disruptions and geoeconomic fragmentation. For policymakers in import-dependent countries, this raises questions about how to de-risk critical supply chains and which industrial policies are best suited to do so.

These questions are important in global markets for rare earth elements (REEs), which saw the introduction of export licensing requirements and industrial policy announcements in 2025. A chokepoint is more likely to emerge when an input is difficult to substitute and three further conditions align: (i) extreme geographic concentration in a single country, (ii) a potential for disruption and, (iii) barriers to rapid diversification. Rare earths satisfy all three. On April 4, 2025, shortly after the U.S. imposed higher import tariffs on most of its trading partners, China — the world's top producer of rare earth elements across all segments of the value chain including mining and refining — introduced export licensing requirements for seven REEs and permanent magnets, citing national security concerns and international non-proliferation obligations (Ministry of Commerce of the People's Republic of China, 2025). These export licensing requirements caused dramatic slowdowns in magnet exports to the rest of the world between April and June, but proved short-lived, with monthly Chinese export volumes quickly returning to their positive trend and displaying double-digit year-on-year growth rates.[1] In response, several countries have launched industrial policies aimed at de-risking REE production.

These supply chain disruptions and new industrial policies to build alternative supply chains all highlight the urgent need to better understand the economics of rare earths. To this end,

[1] After the introduction of the export controls, manufacturers in many countries, including the US, Europe, and India, also began reporting supply disruptions. In October 2025, China announced further tightening of REE controls, later suspended in November under a US–China agreement. In January 2026, China restricted HREE exports to Japan amid a bilateral dispute. Despite these developments, growth in Chinese exports of REE remained strong in January and February 2026.

this paper asks: *how achievable are meaningful levels of REE supply chain de-risking under alternative industrial policy scenarios over the next decade, and at what fiscal cost?* We find that while substantial relative to the size of the market, the fiscal costs associated with the required industrial policies would likely be manageable, particularly under simultaneous actions among various importing countries.[2]

To analyze alternative industrial policies, we develop a calibrated, dynamic trade model of the global rare earths market featuring two stages of production: mining (upstream) and refining (downstream). In the first stage, miners extract raw REE compounds and sell them to refiners on a global market for unprocessed REEs. Refiners then separate these compounds into REE oxides, which are sold on a global market to manufacturers such as permanent magnet producers. In each country/block, a representative miner and a representative refiner invest in productive capacity to maximize profits, taking prices as given.

The model is calibrated to the global market for rare earths by partitioning the world into six countries/regions: the US, China and Myanmar (which, following industry convention, is referred to as China+), Europe, Japan, other Anglophone countries (Canada, Australia), and rest-of-world (RoW). This partitioning reflects each country or region's role in the REE supply chain — as a major producer (China+), a significant consumer (Japan, Europe), a source of untapped mining potential (Anglophone countries), or an economy actively pursuing supply chain de-risking through industrial policy (the US) — with some countries spanning multiple roles.

The model calibration draws on detailed market, industry, and geological data, with particular attention to mining and refining costs across countries. We follow a two-step procedure. First, baseline cost parameters are derived from a breakeven analysis of rare earth projects worldwide. For producers outside China, we evaluate 21 feasibility studies, computing rare earth breakeven prices (in \$/kg) after harmonizing key parameters such as discount rates. For China, breakeven costs are inferred from the 2006–2010 period, when China held a near-monopoly in REE production and the domestic industry was highly competitive, making observed prices a reasonable proxy for marginal costs.[3] Because cost data by production stage in China are not

[2] A companion paper examines the macroeconomic impacts of prolonged REE shortages in the context of a small open economy model with production networks; see Bogmans et al. (2026).

[3] Chinese REE production has more than doubled since 2010, from approximately 120,000 to over 270,000 tons of REO by 2024 (U.S. Geological Survey, 2026), and scale economies may have lowered marginal costs. However,

directly observed, the mining–refining decomposition is implemented transparently as a calibration assumption disciplined by project-level evidence from other producing countries and by the model's price and production targets. Second, taking the baseline cost parameters as given, slope parameters of the cost functions are calibrated to match each country's observed mining and refining production shares. Together, these two steps anchor the cost calibration in both forward-looking project-level estimates and historically revealed cost advantages.

Next, we ask the model to quantify the impact of a major supply disruption, which we proxy by simulating a hypothetical fragmentation of global REE markets into two blocks. We use the model to assess the effects of two industrial policies designed to mitigate the potential macroeconomic effect of the supply disruption :investment subsidies and stylized downstream revenue-support policies (henceforth also referred to as price floors) applied to refining/oxide separation (the most crucial processing stage). We study two implementation scenarios: (1) unilateral action by the United States, in which the policy instruments apply only to U.S.-based producers, and (2) simultaneously among all various net importing countries (U.S., EU, Japan, Australia, and other economies), in which instruments are applied uniformly across participating countries.

To illustrate the trade offs involved with each policy, instruments are calibrated to increase the share of domestic rare earth consumption that is *not* dependent on the largest import source by 15 percentage points in the U.S., from 10 to 25 percent. This measure of diversification can be interpreted as a metric of exposure to the dominant supplier. This is 15 percentage points higher than our baseline at unchanged policies and in line with IEA projections that imply—under announced projects outside China and stated government policies—that diversification levels outside of China would increase by 16 percentage points, from 8 to 24 percent, over the next decade (International Energy Agency, 2025).

The quantitative results from the industrial policy simulations are as follows. First, sizable interventions are needed to attain the 25 percent de-risking targets. For example, in unilateral (simultaneous) scenarios the investment subsidy must cover 74.4 (74.0) percent of total invest-

the industry has undergone significant structural transformation over the same period: environmental regulations were progressively strengthened, culminating in the Rare Earth Management Regulation of 2024; and the number of producers was reduced through consolidation, from several hundred firms to two large groups by 2024 (Bedford, 2025). These changes imply that post-2010 observed prices are less likely to reflect competitive marginal costs.

ment costs to reach the 25 percent de-risking benchmark by 2035. This rises to 88.7 (87.9) percent to achieve 50 percent de-risking. As for revenue-support instrument (price floor), the required policy intervention is also sizable: 2.18x (2.0x) of the period market price for the unilateral (simultaneous) scenario. These large policy interventions reflect the relative efficiency of Chinese producers but also point to important price effects. Because there are already large capacities in both mining and refining, boosting production in a well-supplied market depresses prices and profits, which reduces private investment incentives and, all else equal, requires more generous government interventions to induce additional capacity.

Second, investment subsidies are typically more fiscally efficient than the price floors when evaluated in present-value terms. This reflects the fact that investment subsidies are targeted at new capacity, whereas the revenue-support instrument also generates windfall gains for incumbent producers by supporting existing production. As a result, for a given de-risking target, the net present value of subsidy payments is lower than that of revenue support through price floors. To achieve the 25 percent target under the unilateral (simultaneous) scenario, U.S. fiscal costs associated with the investment subsidy over the first decade amount to 134 (90) percent of the U.S. REE market size—equivalent to about $1.13 billion ($0.76 billion).[4] At the same time, investment subsidies are more costly in the short term than price floors as they front-load fiscal outlays, with costs declining in the long term once investment is largely limited to replacing depreciated capital.

Third, simultaneous action among various importers reduces the fiscal cost of achieving a given de-risking target. For example, when the participating net-REE importing economies simultaneously incentivize investment in refining, individual countries' de-risking is achieved through a less concentrated buildup of capacity, as part of the fiscal cost is outsourced to participating countries. Under simultaneous action, those economies can also leverage the U.S. relatively higher efficiency in REEs processing and see substantial gains in de-risking, at comparatively lower fiscal costs.

Fourth, fiscal costs increase disproportionally with the degree of industrial policy intervention. For example, with higher CAPEX subsidies the U.S. can attain higher levels of de-risking

[4]Global REEs market size is about $6 billion. The U.S. share is 14 percent, so roughly $0.84 billion.

levels in the downstream market, but the fiscal cost increases faster than the attained de-risking rate. This result suggests that very high levels of de-risking can be extremely costly, whereas moderate levels are quickly achievable and at moderate costs.

Contribution to the literature. Our paper contributes to the literature on geoeconomics, which studies how countries leverage economic interdependencies to pursue geopolitical objectives (Clayton et al., 2026). Within this literature, Clayton et al. (2024) develop a theory of economic coercion in which large powers exploit trade and financial dependencies, highlighting the risks of highly concentrated supply chains. Kooi (2025) complements this perspective by formalizing the national security externality — the idea that markets may undervalue resilience in strategic sectors — and quantifies the value of reshoring semiconductor production capacity to the US. On the policy side, Baquie et al. (2025) argue that the effectiveness of industrial policies depends critically on careful design, with poorly targeted interventions yielding limited gains. While these contributions provide useful conceptual frameworks, the literature rarely quantifies the costs and effectiveness of specific policy instruments within particular supply chains, with Kooi (2025) being a notable exception for semiconductors.

We contribute by developing a calibrated dynamic model of the global rare earth supply chain that incorporates investment decisions in both mining and refining capacity and allows the evaluation of alternative policy instruments, including investment subsidies and price floors. The model captures the mining-to-refining bottleneck that characterizes rare earth supply chains, distinguishing between upstream extraction and the technologically more complex refining stage where global supply is most concentrated. Our results provide a cost-based rationale for the thesis in Clayton et al. (2024) that for chokepoint inputs, modest diversification can substantially improve resilience: we find that fiscal costs rise exponentially as de-risking targets increase, so that a small amount of supply chain diversification delivers the largest gains per dollar spent.

A second strand of the literature examines how trade restrictions reshape critical mineral supply chains. Chen (2025) examines mineral export restrictions as a form of industrial policy and finds that such policies reduce upstream exports while sometimes encouraging downstream processing, although empirical evidence of broader industrial upgrading remains limited. Kee

and Xie (2025) study Indonesia's nickel export ban and show that while the policy succeeded in attracting foreign investment and raising the domestic value added ratio of exports, it also led to the entry of less efficient firms, highlighting the unintended allocative costs of such interventions. Turning to rare earths specifically, Alfaro et al. (2025) study how the 2010 REE supply shortage induced directed technological change in downstream industries abroad, increasing efficiency in the use of REEs and reshaping trade patterns in REE-intensive sectors. Shifting to the importer perspective, Shao et al. (2026) shows that a substantial share of global REE consumption occurs indirectly through manufactured goods exported by China, implying that dependence on Chinese REEs is significantly larger than raw mineral trade statistics suggest. Our paper contributes to this literature by developing a quantitative framework that jointly models upstream extraction and downstream processing across countries, allowing us to evaluate how specific industrial policy interventions such as subsidies and price floors reshape global REE production and trade patterns.

A third strand of the literature assesses the criticality of REEs and the macroeconomic consequences of supply disruptions. Nassar et al. (2015, 2020) develop frameworks for assessing mineral supply risk, identifying REEs as among the most strategically exposed inputs due to their concentrated production and importance for high-technology industries.[5] Relatedly, Bogmans et al. (2026) quantify how a REE supply shock propagates through input–output networks, amplifying GDP losses across advanced economies. Our paper builds on these findings by developing a dynamic model of the global REE supply chain that can assess how investment and production decisions respond to policy interventions over time. Rather than tracing the macroeconomic effects through input–output networks as in Bogmans et al. (2026), we study the impact of a market bifurcation on the REE supply chain itself, disentangling the effects on upstream and downstream markets.

The remainder of the paper is structured as follows. Section 2 documents key features of REE markets and supply chains, including the greater geographical concentration in refining than in mining, that motivate the structure of the quantitative model. Section 3 presents a dynamic trade model of global markets for raw and refined REEs, and Section 4 describes the calibration

[5] Nassar et al. (2023) reinforce this point by showing that producing small quantities of refined REE material requires processing large volumes of ore, highlighting some of the structural barriers to expanding supply.

strategy. Section 5 reports the quantitative results, including the effects of different industrial policies in various net-REE importing countries, and the trade-off between fiscal costs and de-risking targets. Section 6 concludes.

2 Descriptive Statistics

This section highlights three key empirical features of REE markets that motivate the structure of the model. First, a small number of elements capture most of the market value. Second, geographical concentration is greater in processing than in mining. Third, this concentration has proved remarkably persistent across several price-spike episodes, particularly in processing.

2.1 The Concentrated Economics of Rare Earths

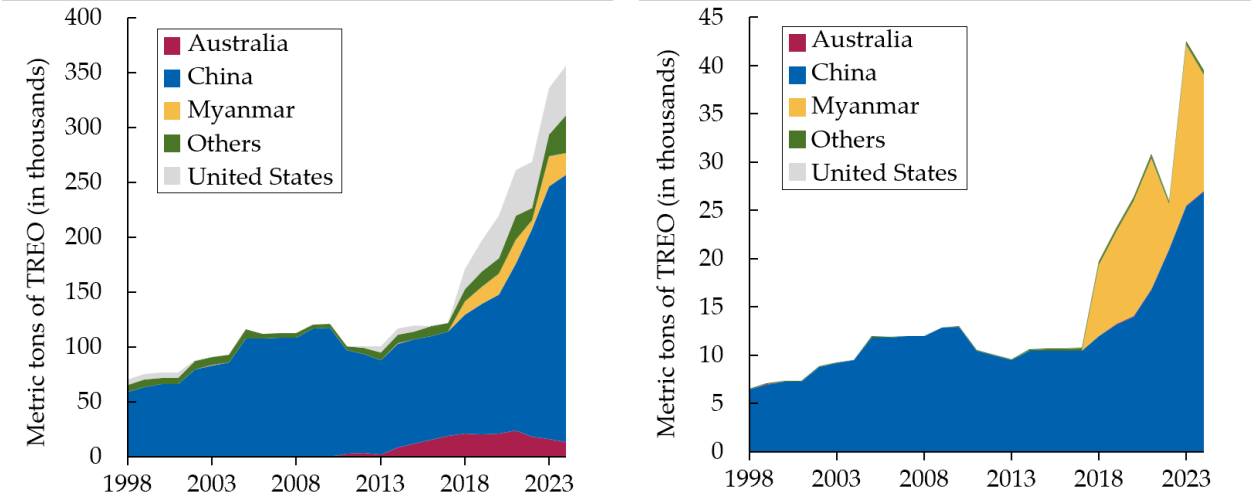
REEs are a group of 17 chemically similar metals, typically grouped into light (LREEs) and heavy (HREEs) based on atomic weight. HREEs are significantly less abundant in the earth's crust than LREEs and typically occur in lower concentrations, making them more difficult to extract at scale. Rare earths are employed in small quantities in various manufacturing sectors including automotive production, wind energy, military applications, semiconductors, and consumer electronics. They provide unique properties that are difficult to replicate cheaply, notably in applications requiring strong magnetic performance, thermal stability, or high-power density.

The economics of rare earths are highly concentrated. Four elements—neodymium (Nd) and praseodymium (Pr), both LREEs, and dysprosium (Dy) and terbium (Tb), both HREEs account for 96 percent of total rare earth oxide (REO) market value despite representing only 23 percent of production by weight (Morgan Stanley Research, 2025). Two forces drive this imbalance. On the demand side, permanent magnets—the fastest-growing application of rare earths—account for roughly 75–85 percent of total REE demand by value (International Energy Agency, 2025).[6] On the supply side, the natural composition of deposits skews production toward high-abundance, low-value elements such as lanthanum and cerium, while the "magnet-4" are produced in much

[6]Permanent magnets arguably constitute the most important application of rare earths; samarium-cobalt magnets are in high demand from the defense sector, while neodymium-iron-boron (NdFeB) magnets are prevalent in electronics, automotive, renewable energy, and other sectors.

smaller quantities. The economic weight of the magnet-4 has risen markedly since 2015, as investments in wind power and electric vehicles following the Paris Agreement have lifted demand for neodymium magnets.[7]

Figure 1: Rare Earth Mining by Country 1998–2024



(a) LREE Production

(b) HREE Production

Sources: Nassar et al. (2023); U.S. Geological Survey (2026); and IMF staff calculations.

Note: Production is measured in thousands of metric tons per year of total rare earth oxide (TREO) mined.

2.2 Global Supply Chain Structure and Concentration by Stage

The rare earth supply chain consists of four sequential stages. Ore is first extracted and transported to nearby benefaction facilities, where mechanical and chemical processes concentrate it into a mixed rare earth compound. This intermediate product is then subjected to solvent extraction, a technically demanding process involving hundreds of sequential separation steps, to isolate individual rare earth elements into oxides or other compounds. In the final stage, these materials are reduced to their metallic form and combined with other inputs to produce alloys, such as NdFeB permanent magnets (U.S. Department of Energy, 2022).

During the 2000s China grew to become the primary source of global rare earth supply,

[7]Permanent magnets rely predominantly on Nd and Pr, which together account for approximately 85 percent of REE inputs in magnet production, with smaller but performance-critical contributions from Dy and, to a lesser extent, Tb (Alonso et al., 2023) (Appendix Table 1).

reflecting technical expertise acquired over decades, a large domestic market, established infrastructure, extensive and farsighted policy support, and relatively flexible regulations. Today, China's primary position varies significantly by rare earth type and supply chain stage. Diversification has been most pronounced for the mining of LREEs: China's share of global LREE mining peaked at roughly 97 percent in 2010 and has since declined to around 58 percent in 2024 (Figure 1) (Nassar et al., 2023; U.S. Geological Survey, 2026). New production from Australia, the United States, and Myanmar has contributed to this shift.[8]

Despite a trend of diversification in the mining of LREEs, China remains the leader over downstream processing stages, accounting for approximately 85–90 percent of global oxide separation capacity and 90–95 percent of metal refining (Figure 2) (Bedford, 2025). Separation is the central technical bottleneck in the supply chain. It is capital- and energy-intensive, environmentally damaging, and requires highly specialized expertise and intellectual property developed over decades. As a result, most rare earth concentrates, regardless of where they are mined, are shipped to China for processing. This limits the extent to which upstream diversification translates into overall supply chain diversification.

Furthermore, for HREEs, concentration is even more extreme and operates at every stage. As shown in Figure 2, which groups China (including Myanmar) accounts for 98 percent of mining, 96.5 percent of oxide separation, 95 percent of metal refining, and 89.5 percent of permanent magnet manufacturing.[9] Unlike LREEs, HREEs face a dual structural bottleneck: mining has seen virtually no geographic diversification, compounding the processing constraints documented above.[10] In short, for LREEs, the critical supply chain vulnerability lies not in mining— which has diversified — but in processing, where concentration remains entrenched. For HREEs, the

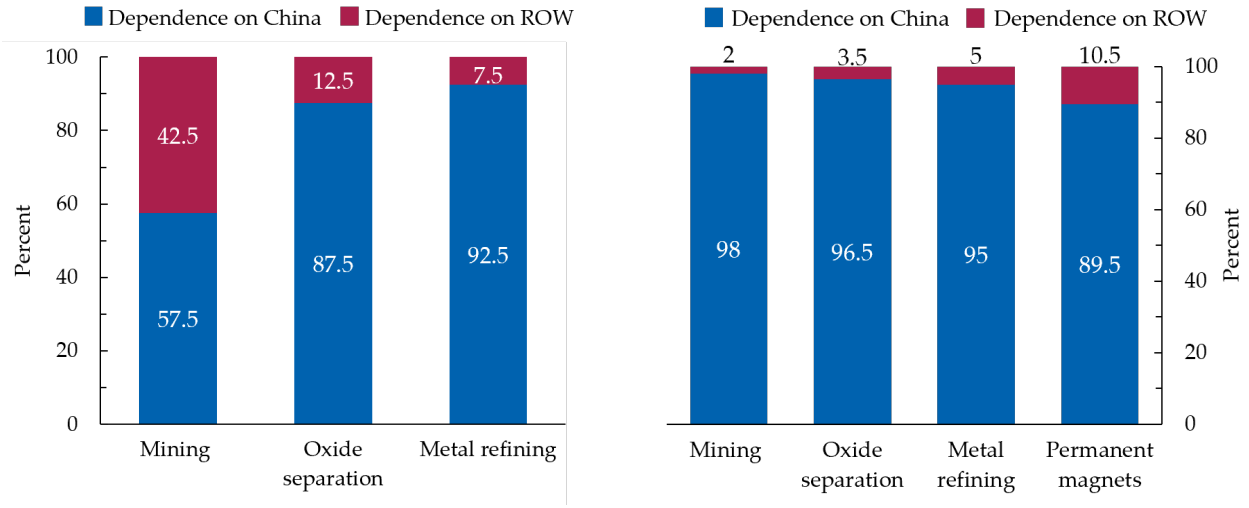
[8]Despite this decline, mining remains highly concentrated, with a small number of large deposits such as China's Bayan Obo mine accounting for a substantial share of global output.

[9]The HREE mining share in Figure 2 (98 percent) differs from Figure 1 (roughly two-thirds) because Figure 1 plots China and Myanmar as separate geographic entities, whereas Figure 2 reports their combined share. The values in Figure 2, drawn from Bedford (2025), measure China's (including Myanmar's) share of global production at each stage of the supply chain, rather than import dependence for any particular consuming country. In contrast, Bogmans et al. (2026) report import dependence measures. The two are therefore not directly comparable. They also differ conceptually: China absorbs approximately 50–60 percent of global refined REE output domestically (Shao et al., 2026), output that counts toward production shares but does not enter international trade. As a consequence, China's net supply of REE to the rest of the world is therefore considerable smaller than gross production data would suggest.

[10]While China dominates permanent magnet manufacturing, this segment presents comparatively lower barriers to capacity expansion, with established producers already operating in the United States, Japan, and Europe — though at smaller scale than in China.

challenge is more fundamental as both mining and processing currently exhibit a high degree of geographic concentration.

Figure 2: Market Share by Source by Rare Earth Supply Chain Segment



(a) LREE Supply Chain Segment

(b) HREE Supply Chain Segment

Sources: Bedford (2025) and IMF staff calculations.

Note: In this figure, "China" refers to China and Myanmar combined. Values reflect production shares by stage; these differ from import dependence measures, which capture net trade exposure. HREE = heavy rare earth element; LREE = light rare earth element; ROW = rest of world.

2.3 Persistence of Concentration: Technology, Costs, and Lead Times

Despite rising demand, some temporary supply shortages, and a wave of industrial policy interventions since 2025, diversification in REE supply chains has remained slow. This persistence reflects the interaction of technological complexity, high capital intensity, and unfavorable project economics outside established production hubs. The concentration in separation and refining in China reflects decades of accumulated technical knowledge and infrastructure that are not easily replicated, while the regulatory burden and specialized expertise required for processing make entry difficult even under favorable market conditions.

New REE projects outside China also face long lead times, typically requiring 10–15 years or more to move from discovery to commercial production, owing to permitting, environmental

regulation, financing, and process development (International Energy Agency, 2025). New entrants must replicate not only physical infrastructure but also the tacit knowledge embedded in production processes, further raising effective entry costs.

Project-level economics reinforce these constraints. A bottom-up assessment of 21 REE projects outside China reveals substantial dispersion in capital and operating costs, with many projects situated on the upper end of the global cost curve (Figure 13). Only a limited number of projects are profitable at current price levels, while many require substantially higher prices to become viable. Historical price dynamics have compounded this problem: following the 2010–2011 price spike, REE prices declined sharply and remained subdued for an extended period, and broader price volatility has since made it difficult to justify the large and irreversible investments required to develop new capacity outside China.[11]

2.4 Industrial Policies

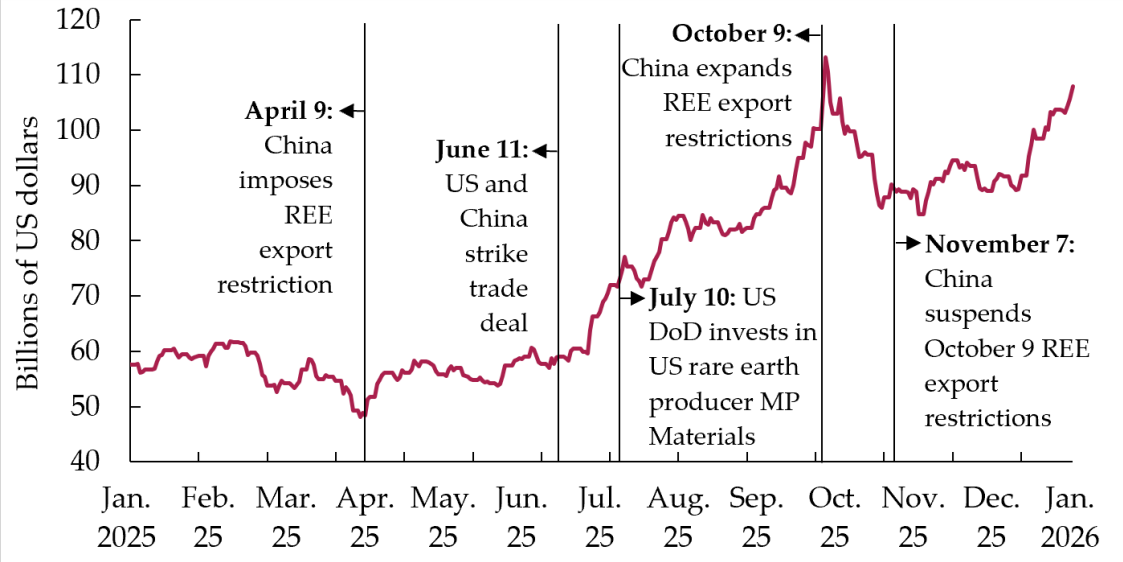
China's introduction of REE export licensing requirements in April 2025 triggered an immediate market slowdown: permanent magnet exports fell by roughly 70 percent year-on-year at the trough, while Dy and Tb prices in European markets nearly tripled by mid-2025. Although monthly Chinese export volumes quickly returned to trend growth—displaying double-digit year-on-year growth rates—the episode was followed by accelerated industrial policy efforts across major economies aimed at de-risking supply chains. It remains to be seen whether these efforts will materially alter existing dependencies.

These efforts have focused on three approaches. First, price floors and offtake agreements have been concluded to provide investment certainty in volatile markets, as many REE projects

[11] While the barriers to diversification documented above are formidable, geological scarcity per se is not among them, at least for LREEs. Global REE reserves outside China exceed 41 million tons of rare earth oxide equivalent, distributed across Brazil, Australia, Russia, Vietnam, United States, and several other jurisdictions (U.S. Geological Survey, 2026), and mine production of LREEs outside of China and Myanmar already reached 98,000 tons in 2025, accounting for 25 percent of global output (U.S. Geological Survey, 2026). For heavy rare earths the picture is fundamentally different: nearly all commercially viable HREE deposits are concentrated in southern China and Myanmar (Bedford, 2025), and current production and proven reserves in other jurisdictions are insufficient to support comparable self-sufficiency targets. That said, proven reserves are not exogenous— Arezki et al. (2019) show that an increase in a country's market orientation leads to a significant increase in mineral discoveries, suggesting that current reserve estimates understate the resource base that would emerge under sustained exploration incentives outside China. HREE supply chain diversification is thus hampered by both geological scarcity and processing concentration, a dimension the current model does not explicitly capture but which constitutes an important avenue for future research.

are not commercially viable at current neodymium prices (about $55/kg). A July 2025 agreement between the U.S. government and MP Materials introduced a price-protection mechanism for key REE products, and price floors more broadly featured prominently in high-level G7 critical minerals discussions. In the quantitative analysis below, we capture this policy family with a stylized revenue-support instrument for refiners; this should be interpreted as a tractable proxy for downside protection rather than as a literal state-contingent contract. Second, governments have provided direct financial support—through equity stakes, loans, and grants—to supply capital and signal long-term commitment. Third, international agreements signed in October 2025 between the United States and Japan, Malaysia, Thailand, and Australia, alongside the G7 Critical Minerals Action Plan, promote joint financing and coordinated procurement, mobilizing an estimated $6.4 billion in public and private funding to de-risk REE supply chains.

Figure 3: Aggregate Stock Market Value of Publicly Listed Firms in the Rare Earth Industry



Sources: S&P Global Market Intelligence (2026a) and IMF staff calculations.

Note: Firms are identified using Capital IQ based on keyword searches for rare-earth-related terms in business and long business descriptions. The sample is restricted to operating, publicly listed companies with primary locations outside China. This initial screen yields 315 firms. Each firm is manually reviewed to retain only those with active involvement in rare earth extraction, processing, or project development. Firms with only peripheral references to rare earths are excluded, resulting in a final sample of 89 companies. REE = rare earth element. DoD = U.S. Department of Defense.

Equity prices of REE producers outside China rallied in July 2025, coinciding with the first major U.S. industrial policy announcement since April's export licensing requirements, suggesting an improvement in market expectations regarding the buildup of supply chains outside China (Figure 3). Motivated by these recent policy developments, in the next section we present a model of sequential production with upstream extraction and downstream refining, and utilize it to study the role of industrial policies aimed at de-risking supply chains.

3 Model

The market of rare earth elements (REEs) is divided in two stages of production, i.e., the *upstream* and the *downstream*. In the first stage of production, raw REEs are extracted by miners and sold to refiners in a global market for raw REEs at the global price p_t^x, i.e., the *upstream price*. Subsequently, refiners transform raw REEs into a refined product that is sold in the global market for refined REEs at the global price p_t^y, i.e., the *downstream price*. There are J countries/blocks in the REE market with a representative miner and a representative refiner in each country $j \in \{0, \ldots, J\}$. In what follows, we refer to miners (refiners) as upstream (downstream) producers and use these terms interchangeably throughout.

3.1 Miners

Each representative REE miner $j \in \{0, \ldots, J\}$ operates competitively (i.e., taking prices as given), by extracting a non-exhaustible endowment of the natural resource x_{jt}. Miners across countries are characterized by differences in extraction costs and investment costs. In the spirit of Anderson et al. (2018) and Kellogg (2024), REE extraction follows an exponential decline with rate $\eta_j > 0$. Letting i_{jt}^x denote the rate of investment in new extraction capacity, the rate of extraction x_{jt} evolves according to the law of motion:

$$x_{jt} = (1 - \eta_j) x_{jt-1} + i_{jt}^x \tag{1}$$

Potentially, each country j can introduce subsidies to extraction capacity and investment in

new extraction capacity.[12] The sequences of mining subsidies $\{s^x_{jt}\}^{\infty}_{t=0}$ and extraction investment subsidies $\{s^{ix}_{jt}\}^{\infty}_{t=0}$ are taken as given by miners. In addition, miners take as given the sequence of upstream REE prices $\{p^x_t\}^{\infty}_{t=0}$. We assume that miners incur two sources of costs: investment in new capacity costs (CAPEX), denoted by $c^{ix}_j(i^x_{jt})$, and extraction costs (OPEX), denoted by $c^x_j(x_{jt})$. We further assume that investment increases extraction capacity immediately, i.e., there is no time-to-build.[13] Letting $\beta_j \in (0,1)$ denote the discount factor, REE extraction in country j is given by the solution to the following problem:

$$\max_{x_{jt}, i^x_{jt}} \sum_{t=0}^{\infty} \beta_j^t \left(\underbrace{p^x_t(1+s^x_{jt})x_{jt}}_{\text{Net revenues}} - \underbrace{(1+s^{ix}_{jt})c^{ix}_j(i^x_{jt})}_{\text{Net CAPEX}} - \underbrace{c^x_j(x_{jt})}_{\text{OPEX}} \right) \tag{2}$$

subject to:

$$x_{jt} = (1-\eta_j)x_{jt-1} + i^x_{jt}$$

$$x_{jt} \geq 0$$

Denoting with λ^x_{jt} the Lagrange multiplier associated with the law of motion of extraction capacity, the optimality conditions of the miners' problem are given by:[14]

$$\lambda^x_{jt} = (1+s^{ix}_{jt})\frac{\partial c^{ix}_j(i^x_{jt})}{\partial i^x_{jt}}$$

$$\lambda^x_{jt} = \beta_j(1-\eta_j)\lambda^x_{jt+1} + p^x_t(1+s^x_{jt}) - \frac{\partial c^x_j(x_{jt})}{\partial x_{jt}}$$

plus (1). The combination of the two first order conditions leads to the simple expression:

[12] We restrict our attention to subsidies to investment in new extraction capacity as this is one of the measure currently discussed. The same logic would apply for total cost subsidies or operational cost subsidies.

[13] The literature has typically studied the one-period time-to-build case. Given that the model is solved using an open-equilibrium approach, removing time-to-build does not affect the mechanism and simplifies the solution of the model.

[14] For exposition purposes we ignore the case in which the $x_{jt} = 0$.

$$\underbrace{(1+s^{ix}_{jt})\frac{\partial c^x_j(i^x_{jt})}{\partial i^x_{jt}}}_{\substack{\text{net current}\\ \text{marginal CAPEX}}} = \underbrace{\beta_j(1-\eta_j)(1+s^{ix}_{jt+1})\frac{\partial c^x_j(i^x_{jt+1})}{\partial i^x_{jt+1}}}_{\text{net future discounted marginal CAPEX}} + \underbrace{p^x_t(1+s^x_{jt}) - \frac{\partial c^x_j(x_{jt})}{\partial x_{jt}}}_{\text{net extraction margin}} \tag{3}$$

where the left-hand side of the (3) represents the (net) marginal cost of one additional unit of CAPEX, and the right-hand side represents its marginal benefit, given by the next-period extraction margin, i.e., the difference between net marginal revenues and marginal OPEX, as well as the discounted savings induced by frontloading CAPEX, i.e., reducing future CAPEX.

For each country j the rate of extraction x_{jt} is determined by the system of equations given by (1) and (3). We define R^s_t as the aggregate quantity of REEs mined in the global market at time t and supplied to refiners, which is defined as:

$$R^s_t \equiv \sum_{j=1}^{J} x_{jt}$$

Notice that x_{jt} is a function of the contemporaneous intermediate price p^x_t.

3.2 Refiners

Similarly to miners, each representative REE refiner $j \in \{0, \ldots, J\}$ operates in a competitive fashion (i.e., taking prices as given). Refiners purchase raw REEs z_{jt} from the global market at the given price p^x_t. Refining raw REEs requires investment in refining capacity y_{jt}, which follows an exponential decline at rate $\delta_j > 0$. Letting i^y_{jt} denote the rate of investment in new refining capacity, the level of refining capacity y_{jt} evolves according to the law of motion:

$$y_{jt} = (1-\delta_j)y_{jt-1} + i^y_{jt} \tag{4}$$

Equivalently to miners, refiners' output y_{jt} is determined by their refining capacity. We also assume that the refining technology is linear in its input and satisfies the equation:

$$y_{jt} = z_{jt} \tag{5}$$

Each country j can introduce subsidies to refining capacity and investment in refining.[15] The sequences of refining subsidies $\{s_{jt}^{y}\}_{t=0}^{\infty}$ and refining investment subsidies $\{s_{jt}^{iy}\}_{t=0}^{\infty}$ are taken as given by refiners. In addition, refiners take as given the sequences of raw REE prices $\{p_t^x\}_{t=0}^{\infty}$ and refined REE prices $\{p_t^y\}_{t=0}^{\infty}$. We assume that refiners incur two sources of costs: capacity investment costs (CAPEX), denoted by $c_j^{iy}(i_{jt}^{y})$, and refining costs (OPEX), denoted by $c_j^{y}(y_{jt})$. Letting $\beta_j \in (0,1)$ denote the discount factor, REE refining in country j is given by the solution to the problem:

$$\max_{z_{jt},y_{jt},i_{jt}^{y}} \sum_{t=0}^{\infty} \beta_j^t \left(p_t^y (1+s_{jt}^{y}) y_{jt} - p_t^x z_{jt} - (1+s_{jt}^{iy}) c_j^{iy}(i_{jt}^{y}) - c_j^{y}(y_{jt}) \right) \tag{6}$$

subject to:

$$y_{jt} = z_{jt}$$

$$y_{jt} = (1-\delta_j) y_{jt-1} + i_{jt}^{y}$$

By combining the first three constraints and replacing them in the profit function, the problem can be rewritten as:

$$\max_{y_{jt}} \sum_{t=0}^{\infty} \beta_j^t \left(\left(p_t^y (1+s_{jt}^{y}) - p_t^x \right) y_{jt} - (1+s_{jt}^{iy}) c_j^{iy}(y_{jt} - (1-\delta_j) y_{jt-1}) - c_j^{y}(y_{jt}) \right)$$

Denoting with μ_{jt} the Lagrangian multipliers associated with the capacity utilization constraint, the first order necessary conditions are given by:

$$\underbrace{(1+s_{jt}^{iy}) \frac{\partial c_j^{iy}}{\partial i_{jt}^{y}}}_{\substack{\text{net current} \\ \text{marginal CAPEX}}} = \overbrace{\underbrace{p_t^y (1+s_{jt}^{y}) - p_t^x}_{\text{gross refining margin}} - \underbrace{\frac{\partial c_j^{y}}{\partial y_{jt}}}_{\substack{\text{net current} \\ \text{marginal OPEX}}}}^{\text{net refining margin}} + \underbrace{\beta_j (1-\delta_j)(1+s_{jt+1}^{iy}) \frac{\partial c_j^{iy}}{\partial i_{jt+1}^{y}}}_{\text{net future discounted marginal CAPEX}} \tag{7}$$

where the left-hand side of (7) represents the (net) marginal cost of one additional unit of CAPEX, and the right-hand side represents its marginal benefit, given by the next-period refining margin,

[15] As for miners, subsidies could cover OPEX or total costs as well.

i.e., the difference between the gross refining margin and the marginal OPEX, as well as the discounted savings induced by frontloading CAPEX, i.e., reducing future CAPEX.

We define R_t^d as the aggregate quantity of raw REE demanded in the global market, which is defined by:

$$R_t^d \equiv \sum_{j=1}^{J} z_{jt} = \sum_{j=1}^{J} y_{jt}$$

Notice that R_t^d is a function of the contemporaneous intermediate price p_t^x.

3.3 Final Good Demands

We assume that each country j demands the processed/refined REE material according to the function:

$$q_{jt} = f(a_{jt}, p_t^y) \tag{8}$$

where $a_{jt} \in \mathbb{R}^+$ is a country-specific and time-specific demand shifter. In the quantitative analysis of the model we will construct a set of demand functions that grow over time, which reflects the anticipated demand growth for refined REEs.

3.4 Equilibrium

Let $\mathcal{J}$ denote the set of all countries in the global REE market. We can then define the competitive equilibrium for the global market as follows:

Definition 1. *Given the initial conditions (x_{j0}, y_{j0}), final demand shifters $\{a_{jt}\}$, and subsidy rate sequences $\{s_{jt}^x, s_{jt}^y, s_{jt}^{ix}, s_{jt}^{iy}\}$ for each country $j \in \mathcal{J}$, a competitive equilibrium for the global REE market is given by allocations $\{x_{jt}, y_{jt}, q_{jt}\}_{j\in\mathcal{J}, t>0}$ and prices $\{p_t^x, p_t^y\}_{t>0}$ such that:*

(i) for each $j \in \mathcal{J}$, the allocations solve the miners' problem (2), the refiners' problem (6), and are consistent with (8);

(ii) the market for raw REEs clears: $\sum_{j\in\mathcal{J}} x_{jt} = \sum_{j\in\mathcal{J}} y_{jt}$;

(iii) the market for refined REEs clears: $\sum_{j\in\mathcal{J}} y_{jt} = \sum_{j\in\mathcal{J}} q_{jt}$.

3.5 Functional Forms

Following the approach of Kellogg (2024), in the remainder of our analysis we assume that the marginal cost of investment in extraction capacity (miners' marginal CAPEX) and the marginal operating cost of extraction (miners' marginal OPEX) are, respectively, given by:

$$\frac{\partial c_j^{ix}}{\partial i_{jt}^{x}} = \alpha_j^{ix} + \gamma_j^{ix}(x_{jt} - (1-\eta_j)x_{jt-1})$$

$$\frac{\partial c_j^{x}}{\partial x_{jt}} = \alpha_j^{x}$$

where α_j^{ix}, γ_j^{ix} and α_j^{x} are country-specific coefficients. Then, country j's supply of raw REEs at time t solves the following second-order difference equation:

$$\begin{aligned} x_{jt} = \Lambda_{jt}^{-1} \Big[& \gamma_j^{ix}(1-\eta_j)(\beta_j(1+s_{jt+1}^{ix})x_{jt+1} + (1+s_{jt}^{ix})x_{jt-1}) - (1+s_{jt}^{ix} - \beta_j(1-\eta_j)(1+s_{jt+1}^{ix}))\alpha_j^{ix} + \\ & + p_t^{x}(1+s_{jt}^{x}) - \alpha_j^{x} \Big] \end{aligned} \tag{9}$$

$$\Lambda_{jt} \equiv \gamma_j^{ix}(1 + s_{jt}^{ix} + \beta_j(1-\eta_j)^2(1+s_{jt+1}^{ix}))$$

In a similar fashion, the marginal cost of investment in refining capacity (refiners' marginal CAPEX) and the marginal operating cost of refining (refiners' marginal OPEX) are, respectively, given by:

$$\frac{\partial c_j^{iy}}{\partial i_{jt}^{y}} = \alpha_j^{iy} + \gamma_j^{iy}(y_{jt} - (1-\delta_j)y_{jt-1})$$

$$\frac{\partial c_j^{y}}{\partial y_{jt}} = \alpha_j^{y}$$

where α_j^{iy}, γ_j^{iy} and α_j^{y} are country-specific coefficients.

Then, country j's demand of raw REEs is given by:

$$
\begin{aligned}
y_{jt} = \zeta_{jt}^{-1} \Big[\gamma_j^{iy}(1-\delta_j)(\beta_j(1+s_{jt+1}^{iy})y_{jt+1} + (1+s_{jt}^{iy})y_{jt-1}) - (1+s_{jt}^{iy} - \\
-\beta_j(1-\delta_j)(1+s_{jt+1}^{iy}))\alpha_j^{iy} + p_t^y(1+s_{jt}^y) - p_t^x - \alpha_j^y \Big] \\
\zeta_{jt} \equiv \gamma_j^{iy}(1+s_{jt}^{iy} + \beta_j(1-\delta_j)^2(1+s_{jt+1}^{iy}))
\end{aligned}
\tag{10}
$$

We assume that the individual country j's demand for the refined REE product is given by the isoelastic static demand function:

$$
q_{jt} = a_{jt} \left(p_t^y\right)^{-\epsilon}
$$

where, as already defined, a_{jt} is the demand shifter and $\epsilon \in \mathbb{R}^+$ is the elasticity of substitution of the demand with respect to its price, which is assumed to be common across all countries. Then, the world's aggregate demand for refined REEs is given by:

$$
Q_t = \sum_{j=1}^{J} q_{jt} = A_t \left(p_t^y\right)^{-\epsilon}
$$

where $A_t \equiv \sum_{j=1}^{J} a_{jt}$ is the aggregate demand shifter for refined REEs.

3.6 Steady State Equilibrium

We construct the steady state of the model in which no industrial policies are implemented, i.e., $s_j^x, s_j^{ix}, s_j^y, s_j^{iy} = 0$ for all $j \in \mathcal{J}$. Furthermore, we assume that the discount factor and the depreciation rates for miners and refiners are common across countries. Let $\beta \equiv \frac{1}{1+r}$, where r is the discount rate. Then, the steady state of the model is characterized by the following equations. On the supply side, mining output by producer j is given by:

$$
x_j = \frac{p^x - \alpha_j^x - \beta^x \alpha_j^{ix}}{B_j^x} \tag{11}
$$

where $\beta^x \equiv 1 - \beta(1-\eta) = \frac{r+\eta}{1+r}$ and $B_j^x \equiv \gamma_j^{ix} \eta \beta^x$. Processing output is:

$$y_j = \frac{p^y - p^x - \alpha_j^y - \beta^y \alpha_j^{iy}}{B_j^y} \tag{12}$$

where $\beta^y \equiv 1 - \beta(1-\delta) = \frac{r+\delta}{1+r}$ and $B_j^y \equiv \gamma_j^{iy} \delta \beta^y$. On the demand side, aggregate demand is:

$$Q = A(p^y)^\epsilon \tag{13}$$

where $A \equiv \sum_j a_j$. Market clearing requires $Q = Y$ and material balance requires $Y = X$, where $Y \equiv \sum_j y_j$ and $X \equiv \sum_j x_j$.

The equilibrium prices satisfy two conditions. First, the mining price as a function of the processed material price is:

$$p^x = \frac{p^y \Gamma^y - \Psi^y + \Theta^x}{\Gamma^y + \Gamma^x} \tag{14}$$

Second, the processed material price satisfies the nonlinear equilibrium condition:

$$A(p^y)^\epsilon (\Gamma^y + \Gamma^x) + \Theta^x \Gamma^y + \Psi^y \Gamma^x = p^y \Gamma^y \Gamma^x \tag{15}$$

or, stated otherwise:

$$A(p^y)^\epsilon = \frac{\left(p^y \Gamma^y - \Psi^y\right) \Gamma^x - \Theta^x \Gamma^y}{\Gamma^y + \Gamma^x} \tag{16}$$

The parameter bundles are defined as follows:

- $\Gamma^y \equiv \sum_j \frac{1}{B_j^y} = \sum_j \frac{1}{\gamma_j^{iy} \delta \beta^y}$ (aggregate processing supply responsiveness)
- $\Psi^y \equiv \sum_j \frac{\alpha_j^y + \beta^y \alpha_j^{iy}}{B_j^y}$ (weighted processing costs)
- $\Gamma^x \equiv \sum_j \frac{1}{B_j^x} = \sum_j \frac{1}{\gamma_j^{ix} \eta \beta^x}$ (aggregate mining supply responsiveness)
- $\Theta^x \equiv \sum_j \frac{\alpha_j^x + \beta^x \alpha_j^{ix}}{B_j^x}$ (weighted mining costs)

4 Calibration

In this section we describe the calibration strategy used to derive the quantitative implications of the global REE market model.

4.1 Calibration overview

We calibrate the model to a 2024 base year using data from publicly available feasibility studies, industry reports, and the academic literature. The calibration proceeds in four steps. First, we fix the demand elasticity and country-level demand shifters using published elasticity estimates and observed consumption shares. Second, we set the cost intercept parameters—operating costs (α_j^x, α_j^y) and investment cost intercepts (α_j^{ix}, α_j^{iy})—using a breakeven analysis of rare earth projects.[16] Where separate cost evidence for mining and refining is unavailable—as is the case for several major producers, including China—the decomposition should be read as an explicit calibration assumption rather than as a directly observed accounting split. Third, we decompose the investment cost slope parameters in two-parts: a common element κ^{is} and a country-specific element $\bar{\gamma}_j^{is}$, such that $\gamma_j^{is} = \kappa^{is}\bar{\gamma}_j^{is}$ for $s = \{x, y\}$. We then calibrate the investment cost slope parameters ($\bar{\gamma}_j^{ix}$, $\bar{\gamma}_j^{iy}$) to match observed mining and refining production shares across regions. Fourth, we pin down two remaining scale parameters (κ^{ix}, κ^{iy}), which govern the absolute level of equilibrium prices. Table 1 summarizes all parameter values.

4.2 Demand Parameters

The short-run price elasticity of demand for refined REEs is set to $\varepsilon = -0.15$, based on the unweighted average of elasticity estimates for the four magnet REEs (Nd, Pr, Dy, Tb) from Shojaeddini et al. (2025). This low elasticity reflects the essential role of these elements in permanent magnets and the limited substitutability of REEs in downstream applications over short horizons.[17]

[16] See Appendix A for a detailed breakeven analysis of REE projects.

[17] Material choices are deeply embedded in engineering design: an EV motor built around a neodymium-based permanent magnet cannot switch to an alternative material without redesigning the motor architecture and undergoing re-certification. Input intensity is correspondingly fixed at the design stage, with each EV motor requiring 1–2 kg of permanent magnet material and offshore wind turbines often exceeding 500–600 kg of rare earth elements per unit (Gielen and Lyons, 2022). Substitution constraints are particularly binding for Dy and Tb, which score approximately

Country-level demand shares are constructed as follows. China accounts for 50 percent of global refined REE consumption in the base year, following Shao et al. (2026). The remaining 50 percent is allocated across other regions in proportion to their shares of Chinese REE exports in 2019 (also from Shao et al. (2026)). Given these shares and the isoelastic demand specification $q_j = a_j(p^y)^\varepsilon$, we back out the demand shifters a_j that rationalize observed 2024 consumption at the equilibrium refined price. We then solve the model using the standardized demand shifters given by $\bar{a}_j \equiv \frac{a_j}{\sum_j a_j}$, which allow us to express each country's demand as a share of total world demand when the price of the refined good equals 1.

Demand growth rates are taken from the IEA Global Critical Minerals Outlook (International Energy Agency, 2025), which projects annual growth of 4.7 percent during 2025–2029, 1.47 percent during 2030–2034, and zero thereafter. In the model, these enter as exogenous shifts in the demand parameters a_j over time, preserving relative country shares.

4.3 Cost Intercept Parameters

The model features four cost intercept parameters per region: operating costs for mining (α_j^x) and refining (α_j^y), and investment cost intercepts for mining (α_j^{ix}) and refining (α_j^{iy}). We calibrate these using a two-step procedure that first recovers integrated breakeven prices and then decomposes them across the two supply chain stages.

Breakeven methodology. For producers outside of China, we evaluate 21 rare earth projects with published feasibility studies. For each project, we compute the NdPr-equivalent breakeven price—the constant real price at which net present value equals zero under an 8 percent real discount rate—taking into account operating expenditures (OPEX), upfront capital expenditures (CAPEX), mine life, annual production volumes, and project-specific payability assumptions.[18] The representative breakeven price outside of China, expressed in 2024 USD per kilogram of NdPr, is \$77/kg, of which \$43/kg reflects operating costs and \$34/kg reflects the annualized

78 out of 100 on substitutability indices compared to an average of 57 for non-REE materials (Graedel et al., 2015).

[18] Payability refers to the fraction of total rare earth oxide (TREO) output with commercial value. Because REE deposits contain a geologically fixed mix of light and heavy elements, only a subset of the extracted oxides—primarily Nd, Pr, Dy, and Tb—commands significant market prices. Our breakeven analysis accounts for each project's specific output mix and the commercial value of its payable fraction. See Appendix A.

capital charge.

We map the capital component into the model's investment cost intercept using the user-cost identity:

$$\text{CAPEX annuity} = \frac{r+\eta}{1+r}\,\alpha_j^i, \tag{17}$$

where $r = 0.08$ is the discount rate and $\eta = 0.035$ is the annual depreciation rate of productive capacity.[19] This expression reflects the annual cost of maintaining one unit of productive capacity: each year, a fraction η of capacity depreciates and must be replaced, and the capital tied up in the investment carries an opportunity cost of r. Inverting equation (17) yields $\alpha_j^i = \text{CAPEX annuity} \,/\, \left(\frac{r+\eta}{1+r}\right)$.[20] Applied to the integrated capital charge of \$34/kg, this gives a total investment cost intercept for producers outside of China of $\alpha^i = 34/0.1065 \approx 318$ USD/kg of annual NdPr capacity.

Mining–refining decomposition. Because the model distinguishes between upstream mining and midstream oxide separation, we decompose the integrated cost estimates into stage-level parameters. This requires two assumptions, both guided by project-level data and industry evidence.[21]

First, we allocate 70 percent of operating costs to mining and 30 percent to refining, reflecting the relatively higher labor, energy, and material costs associated with extraction and beneficiation. Since the operating cost intercepts in the model correspond directly to per-kilogram operating costs, this yields $\alpha^x \approx 30$ USD/kg and $\alpha^y \approx 13$ USD/kg.[22] Second, we allocate 40 percent of annualized capital costs to mining and 60 percent to refining. The heavier capital weight on refining reflects the high capital intensity of chemical separation plants relative to extraction. Applying equation (17) to each stage separately yields the investment cost intercepts $\alpha^{ix} \approx 127$

[19] We assume a common depreciation rate η across mining and refining, reflecting the typical useful life of both extraction and chemical separation facilities.

[20] Under the baseline values $r = 0.08$ and $\eta = 0.035$, this gives $(r+\eta)/(1+r) = (0.08+0.035)/1.08 \approx 0.1065$.

[21] O'Brien and Alonso (2025) develop a regression-based cost model for REE mining projects that distinguishes projects by processing depth: those producing a mixed rare earth chemical product (B+C/L) and those extending through advanced oxide separation (B+C/L+A). Advanced separation corresponds to the refining stage in our model. At comparable project scales, their estimates imply that the refining stage accounts for approximately 32 percent of a fully integrated project's total operating costs and 67 percent of its total capital expenditures. We allocate 30 percent of operating costs and 60 percent of capital costs to refining, both conservative relative to these estimates.

[22] Computed as $0.70 \times 43 \approx 30$ and $0.30 \times 43 \approx 13$ USD/kg, respectively.

USD/kg and $\alpha^{iy} \approx 191$ USD/kg.[23] Under this decomposition, mining accounts for approximately 56 percent of the integrated breakeven cost outside of China, and refining for 44 percent.[24] The resulting parameter values are $\alpha^{x} = 30$, $\alpha^{ix} = 127$, $\alpha^{y} = 13$, and $\alpha^{iy} = 191$ USD/kg for all regions outside of China.

We then normalize all cost intercepts by α^{iy}, the marginal investment cost of refiners outside of China, and denote the transformed variables with a "bar." [25] Hence, for all economies outside of China, the parameter values are $\bar{\alpha}^{x} = 30/191$, $\bar{\alpha}^{ix} = 127/191$, $\bar{\alpha}^{y} = 13/191$, and $\bar{\alpha}^{iy} = 191/191$.

Chinese cost parameters. For China, we anchor the calibration to the historical median NdPr price of \$42.5/kg (in 2024 dollars), inferred from the 2006–2010 period during which China held a near-monopoly in REE production and the industry had not yet undergone state-led consolidation. Under these conditions, competition among firms drove prices toward marginal cost, making observed prices a reasonable proxy for breakeven costs.

Decomposing this single breakeven into stage-level cost parameters requires three assumptions. First, we assume that 75 percent of this breakeven reflects operating costs and 25 percent capital costs, consistent with China's established infrastructure, scale efficiencies, and accumulated process know-how. This implies total operating costs of approximately \$31.9/kg and a total annualized capital charge of approximately \$10.6/kg.[26] Applying equation (17) to the total capital charge gives a total investment cost intercept of $\alpha^{i} \approx 99$ USD/kg.[27]

Second, to decompose across supply chain stages, we allocate roughly 69 percent of China's total breakeven cost to mining and 31 percent to refining, yielding stage-level total costs of ap-

[23] The mining capital annuity is $0.40 \times 34 \approx 13.6$ USD/kg, giving $\alpha^{ix} = 13.6 / 0.1065 \approx 127$ USD/kg. The refining capital annuity is $0.60 \times 34 \approx 20.4$ USD/kg, giving $\alpha^{iy} = 20.4 / 0.1065 \approx 191$ USD/kg.

[24] Computing the present value of operating costs relative to upfront capital expenditures for each of the 21 projects confirms that operating costs systematically exceed capital costs, with a sample median OPEX share of 69 percent and an interquartile range of 65 to 79 percent. The wide dispersion reflects heterogeneity in project scale, geological setting, and processing depth. Among the most capital-intensive projects—those planning full oxide separation and requiring the largest upfront investments—OPEX shares fall to the 59–64 percent range, consistent with the cost structure embedded in the representative breakeven price. Results are robust to the exclusion of outliers at both ends of the distribution. The decomposition across supply chain stages requires additional assumptions.

[25] This normalization sets the scale of the model so that all costs are expressed relative to the most capital-intensive activity in the supply chain, ensuring that cross-country cost comparisons reflect relative rather than absolute magnitudes.

[26] Computed as $0.75 \times 42.5 \approx 31.9$ and $0.25 \times 42.5 \approx 10.6$, respectively.

[27] Computed as $10.6 / 0.1065 \approx 99$; see footnote 20 for the derivation of the conversion factor.

proximately \$29.3/kg for mining and \$13.2/kg for refining.[28] This allocation is a calibration assumption reflecting China's disproportionately strong cost advantage in refining, so that refining accounts for only 31 percent of total costs in China, compared to 44 percent in projects outside of China.

Third, guided by the higher capital intensity of oxide separation relative to extraction, we allocate approximately 30 percent of the annualized capital charge to mining and 70 percent to refining. This is a calibration assumption motivated by the fact that even in China, oxide separation remains more capital-intensive than extraction, requiring specialized solvent extraction circuits and environmental containment infrastructure. Applying equation (17) to each stage separately yields $\alpha^{ix} \approx 30$ USD/kg and $\alpha^{iy} \approx 69$ USD/kg.[29] The operating cost intercepts follow residually: subtracting each stage's annualized capital charge from its total cost gives $\alpha^{x} \approx 26$ USD/kg and $\alpha^{y} \approx 6$ USD/kg.[30]

A notable feature of this calibration is that the majority of the total cost gap between Chinese producers and those outside China—approximately 58 percent—originates in the refining stage rather than mining.[31] This pattern is consistent with the well-documented concentration of China's technological advantage in oxide separation, the most technically demanding and capital-intensive segment of the rare earth supply chain (Bedford, 2025). We then normalize the cost intercepts of Chinese miners and refiners. This yields $\bar{\alpha}^{x} = 26/191$, $\bar{\alpha}^{ix} = 30/191$, $\bar{\alpha}^{y} = 6/191$, and $\bar{\alpha}^{iy} = 69/191$.

Cost uniformity outside of China. We assume identical cost parameters across all regions outside China. Our evaluation of 21 projects reveals that, while these projects are on average substantially less competitive than Chinese production, there is little evidence of a systematic cost ranking across non-Chinese producers. This assumption simplifies the calibration and focuses cross-country variation on differences in production scale, as captured by the investment slope

[28] Computed as $0.69 \times 42.5 \approx 29.3$ and $0.31 \times 42.5 \approx 13.2$, respectively.

[29] The mining capital annuity is $0.30 \times 10.6 \approx 3.2$ USD/kg, giving $\alpha^{ix} = 3.2 \,/\, 0.1065 \approx 30$. The refining capital annuity is $0.70 \times 10.6 \approx 7.4$ USD/kg, giving $\alpha^{iy} = 7.4 \,/\, 0.1065 \approx 69$. See footnote 20 for the derivation of $(r+\eta)/(1+r) \approx 0.1065$.

[30] Computed as $\alpha^{x} = 29.3 - 3.2 \approx 26$ and $\alpha^{y} = 13.2 - 7.4 \approx 6$.

[31] The total breakeven gap is approximately $\$77 - \$42.5 = \$34.3$/kg. Of this, the refining cost differential accounts for $\$33.3 - \$13.4 \approx \$20.0$/kg, or 58 percent, with the remaining 42 percent attributable to mining.

parameters.

4.4 Investment Slope Parameters

The investment cost slope parameters γ_j^{ix} and γ_j^{iy} govern the convexity of investment costs and thereby influence the equilibrium scale of production in each region. First, we define $\gamma_j^{is} \equiv \kappa^s \bar{\gamma}_j^{is}$ for each sector $s = \{x, y\}$, where $\kappa^s > 0$ is common across all countries and $\bar{\gamma}_j^{is} > 0$ is country-specific. We calibrate these parameters to match observed 2024 mining and refining production shares, with the U.S. normalized to $\bar{\gamma}_{\text{US}}^{ix} = \bar{\gamma}_{\text{US}}^{iy} = 1$.

Identification. The key identification argument is that, in steady state, relative production levels across regions are determined by the ratios of γ parameters. To see this, consider two regions outside of China, j and m, with identical cost intercepts. From the steady-state mining expression, $x_j = (p^x - \alpha^x - \beta^x \alpha^{ix})/(\gamma_j^{ix}\, \eta\, \beta^x)$, it follows that

$$\frac{x_j}{x_m} = \frac{\gamma_m^{ix}}{\gamma_j^{ix}}. \tag{18}$$

Because cost parameters are identical across all regions outside China, gross profit margins cancel, and relative output depends only on the inverse ratio of slope parameters. An analogous relationship holds for refining. Normalizing $\bar{\gamma}_{\text{US}}^{ix} = 1$, the slope parameter for any region outside of China, j, is therefore

$$\bar{\gamma}_j^{ix} = \frac{x_{\text{US}}}{x_j}, \tag{19}$$

where x_j denotes the 2024 mining production share of region j. A similar argument holds for refining.

China. For China, the same logic applies but the cost intercepts differ from those outside China, so gross margins no longer cancel. Taking ratios of the steady-state expressions for China and the U.S. yields

$$\bar{\gamma}_{\text{CHN}}^{ix} = \frac{x_{\text{US}}}{x_{\text{CHN}}} \cdot \frac{p^x - \alpha_{\text{CHN}}^x - \beta^x\, \alpha_{\text{CHN}}^{ix}}{p^x - \alpha_{\text{US}}^x - \beta^x\, \alpha_{\text{US}}^{ix}}, \tag{20}$$

and analogously for refining. Evaluating this expression requires the equilibrium mining price p^x, which depends on all model parameters through the steady-state price conditions. In practice, we compute γ^{ix}_{CHN} jointly with the price-level calibration described in the next subsection.

Zero-production regions. Several regions exhibit zero production in one segment of the supply chain in the base year: the EU and Japan have no mining, while the Anglophone region has no refining. In these cases, the γ parameter is not identified by equation (18). We therefore assign large values to these parameters, reflecting prohibitively high investment adjustment costs consistent with the absence of current production. Operationally, these values are chosen so that zero-production regions remain inactive at the initial price vector; the global material balance condition $X = Y$ is then satisfied by market clearing rather than by these parameters per se.

4.5 Price-Level Calibration

The procedure in Section 4.4 pins down the *relative* γ parameters across regions but leaves their absolute scale—and hence the level of equilibrium prices—undetermined. We close the calibration by introducing two scaling parameters, κ^{ix} and κ^{iy}, which multiply all mining and refining slope parameters, respectively. Formally, the effective investment cost slope for region j in mining is $\kappa^{ix}\tilde{\gamma}^{ix}_j$, and analogously $\kappa^{iy}\tilde{\gamma}^{iy}_j$ for refining.

These parameters are identified by using two equilibrium price targets. First, we numerically match the refined price to $p^y = 1$ in the initial steady state, which serves as a normalization of the unit of account.[32] Second, we target a mining-to-refining price ratio of $p^x/p^y = 0.55$, so that the mining stage receives 55 percent of integrated revenues in steady state. This ratio is consistent with our breakeven decomposition, which attributes approximately 55 percent of total costs to the mining segment, for both Chinese producers and those outside of China.

Given all other parameters, κ^{ix} and κ^{iy} are jointly determined by the steady-state equilibrium price conditions. The calibrated values are $\kappa^{ix} = 600$ and $\kappa^{iy} = 5{,}000$.

[32] Because the model is solved in terms of a composite NdPr-equivalent unit, normalizing $p^y = 1$ amounts to expressing all monetary quantities in units of the refined product's base-year value.

4.6 Numerical Algorithm

Given the model parameters, we first compute the deterministic steady state of the economy in the absence of industrial policy. We begin with an initial guess for the final good price and solve for the optimal steady-state levels of mining and refining capacity for each economy over a grid of intermediate good prices p^x. For each point on the grid, we construct aggregate demand and supply and compute the equilibrium price such that excess supply of raw REEs is zero. We then obtain the final good price, update our initial guess, and iterate until convergence. Next we solve for the model dynamics in a similar fashion, using an open-loop equilibrium approach, i.e., one in which the paths of all policies are determined at time $t = 0$. We start from the initial conditions $\{x_{j,-1}, y_{j,-1}\}_{j=1}^{J}$ and construct initial guesses for the time path of the final good price, $\{p_t^{0,y}\}_{t=0}^{T}$, as well as for the state variables, $\{x_{j,t}^0\}_{j,t}$ and $\{y_{j,t}^0\}_{j,t}$. Given these guesses, we solve the system of difference equations forward for each point on the intermediate good price grid and compute the equilibrium price at each date t. We then use the equilibrium prices and quantities obtained from the model to update the guessed price path and state variables, and iterate until convergence.

4.7 Summary

Table 1 reports the complete set of calibrated parameters. Several features of the calibration merit emphasis. First, the cost intercepts embed a large competitive gap between producers in China and those in other regions, with roughly half of this gap concentrated in the refining stage. Second, China's low γ values reflect its dominant production shares—the investment cost function is relatively flat, allowing China to scale capacity at low marginal adjustment cost. Third, the high γ values for regions with zero production imply that entry would require substantial policy intervention to overcome steep investment costs, a feature that is central to the policy experiments analyzed in the following sections. Fourth, the model is solved using standardized parameters only, i.e., parameters denoted with a bar.

We also report the results of the matching moments exercise used to obtain the baseline calibration in Table 2. As noted above, $\bar{\gamma}^{ix}_{\text{CHINA}}$ is chosen to match China's steady-state in mining, which is approximately 0.8. Given the construction of the remaining marginal mining CAPEX

parameters, this procedure also allows us to recover the exact mining shares of all the other countries/blocks. Similarly, we choose $\bar{\gamma}^{iy}_{\text{CHINA}}$ to match China's steady-state share in refining, which is approximately 0.91. Finally, we set κ^{ix} and κ^{iy} to normalize the steady-state price of the refined product p^y_{SS} to 1, and obtain a relative price of the mined product p^x_{SS}/p^y_{SS} around 0.55.

The next section presents the quantitative results of the baseline model and analyzes the effects of alternative industrial policies on the refining sector.

5 Quantitative Results

This section analyzes the quantitative implications of the global REE model described in this paper. First, we begin by presenting the results arising from simulating the model under current policies. We further expand the discussion of the structure of the global REE market by examining the supply and demand elasticities. Second, we describe the consequences of a potential global REE supply shock. Third, we discuss the effects of introducing different industrial policies in net importing economies, focusing our attention on the special case of the US.[33] Fourth, we show that the fiscal cost of industrial policies is convex in the degree of attained de-risking. Throughout this section we refer to "importing countries" and "economies outside China" interchangeably as in the special case of REEs, and given the current market structure, the two groups coincide.

5.1 Baseline Results

Using the calibration strategy outlined above, we simulate the model for a period of $T = 150$ years starting in 2025.[34] In the model we use as initial conditions the observed levels of mining and refining quantities in 2024, outlined in Table 1. We feed the model with the anticipated demand growth rates described in Table 1 and construct the paths of mining and refining output, final good demand, and price levels. We report the results of the baseline in Figure 4.

The projected increase in demand raises mining and refining production across all the economies,

[33] Similar results would hold also for other importing economies (e.g., Japan and the EU).

[34] The proposed horizon is sufficiently long to allow us to converge to steady-state values while minimizing the computational efforts.

Table 1: Model Calibration Parameters by Country/Region

Parameter		Units	U.S.	China+	EU	Japan	Anglophone	RoW
Demand parameters								
Demand shifter	a_j	kt/yr	21.3	76.6	21.0	14.0	1.4	18.9
Price elasticity of demand	ε					-0.15		
Annual growth 2025–29, 2030–34, $\geq$2035		% per yr				4.7, 1.47, 0		
Common parameters								
Discount rate	r					0.08		
Depreciation rate	η					0.035		
Mining cost parameters								
Operating cost intercept	α_j^x	\$/kg	30	26	30	30	30	30
Investment cost intercept	α_j^{ix}	\$/kg/yr	127	30	127	127	127	127
Investment cost slope	$\bar{\gamma}_j^{ix}$		1	0.195	200	200	2.4	6.57
Scaling parameter	κ^{ix}					600		
Refining cost parameters								
Operating cost intercept	α_j^y	\$/kg	13	6	13	13	13	13
Investment cost intercept	α_j^{iy}	\$/kg/yr	191	69	191	191	191	191
Investment cost slope	$\bar{\gamma}_j^{iy}$		1	0.02	1.68	1.68	100	0.21
Scaling parameter	κ^{iy}					5 000		
Base-year production (2024)								
Mining output		kt/yr	43.0	285.8	0.0	0.0	18.0	6.5
Refining output		kt/yr	1.13	86.72	0.67	0.67	0.00	5.42

Notes: All quantities are expressed in NdPr-equivalent units. Monetary values are in 2024 USD. Mining production data from U.S. Geological Survey (2025); refining data from International Energy Agency (2025). The demand shifters a_j are calibrated to rationalize observed consumption at the initial steady-state refined price $p^y = 1$. The investment cost slopes γ_j^{ix} and γ_j^{iy} are reported before multiplication by κ^{ix} and κ^{iy} respectively.

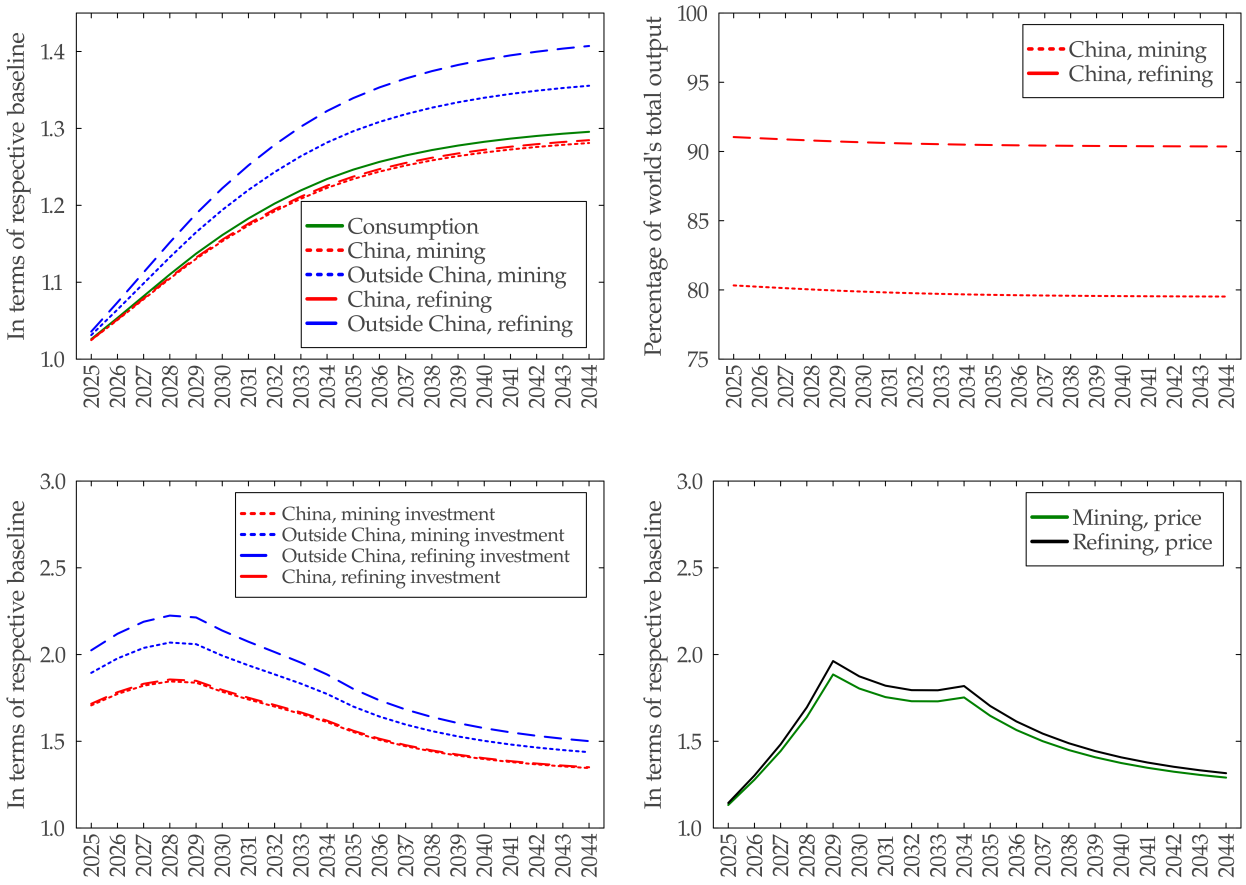
Table 2: Calibration: Matched Parameters

Parameter	Moment	Target	Value
$\bar{\gamma}^{ix}_{\text{CHINA}}$	China's mining share, steady state	0.80	0.81
$\bar{\gamma}^{iy}_{\text{CHINA}}$	China's refining share, steady state	0.91	0.92
p^{y}_{SS}	Price of refined product, steady state	1.0	0.96
$p^{x}_{\text{SS}}/p^{y}_{\text{SS}}$	Refined-to-mined product price ratio, steady state	0.55	0.55

with only modest changes in their distributions across countries. In the case of the U.S., the increase in refined REE production leads to only a marginal improvement in de-risking relative to China. The price of the refined REE good increases on impact to accommodate the initial excess demand from consumers, and rises further during the period of stronger demand between 2030 and 2034. As demand growth stabilizes and investment in mining and refining increases, prices begin to decline and converge to a new steady state. In the new steady state, equilibrium prices remain higher, due to the quadratic functional forms of OPEX and CAPEX.

The increase in demand stimulates further mined and refined output through higher CAPEX investment in both stages. In particular, investment in refining capacity is stronger. Interestingly, demand growth leads to faster growth in economies outside China. Intuitively, by considering (11) and (12), and noting that marginal OPEX and CAPEX are linear, demand growth leads to higher net mining and refining profit margins. Prior to demand growth, producers outside China, and in particular refiners, faced thinner margins compared to their Chinese competitors. Hence, the improvement in profit margins is relatively larger for these economies, allowing them to capture a greater share of the increased demand for the final product. This is confirmed by the observation that investment grows faster outside China and that the new steady state rate of investment is higher. The top right panel in Figure 4 shows that Chinese market leadership in mining and refining is reduced, although by a small margin. Moreover, demand growth leads to persistently higher price levels for both upstream and downstream products, with initially higher prices driven by strong investment needs and supply rigidities.

Figure 4: Baseline evolution



Industry Elasticities - The global REE market is characterized by slow adjustments in production quantities. We investigate the degree of rigidity in both upstream and downstream segments of the market by analyzing demand and supply elasticities for both miners and refiners, in both the short-run and the long-run. We denote by $\mathcal{E}^d_{j,i,z}$ the demand elasticity of country j for product $i \in \{x, y\}$ at horizon $z \in \{\text{SR,LR}\}$, where SR indicates short-run and LR indicates long-run. Similarly, we denote by $\mathcal{E}^s_{j,i,z}$ the corresponding supply elasticity. The analysis holds cross-prices and past and future quantities fixed at their steady state levels. In order to compute the short-run supply and demand elasticities we use (9) and (10), which yield the following expressions for elasticities:

$$\mathcal{E}^s_{j,x,SR} = \frac{p^x}{\gamma^{ix}_j(1-\eta_j)(\beta_j x_{ss,j} + x_{ss,j}) - (1-\beta_j(1-\eta_j))\alpha^{ix}_j + p^x - a^x_j}$$

$$\mathcal{E}^{d}_{j,x,SR} = -\frac{p^x}{\gamma^{iy}_j(1-\delta_j)(\beta_j y_{ss,j} + y_{ss,j}) - (1-\beta_j(1-\delta_j))\alpha^{iy}_j + p^y_{ss} - p^x - a^y_j}$$

$$\mathcal{E}^{s}_{j,y,SR} = \frac{p^y}{\gamma^{iy}_j(1-\delta_j)(\beta_j y_{ss,j} + y_{ss,j}) - (1-\beta_j(1-\delta_j))\alpha^{iy}_j + p^y - p^x_{ss} - a^y_j}$$

$$\mathcal{E}^{d}_{j,y,SR} = -\epsilon$$

In a similar fashion, using (11) and (12) we obtain the long-run elasticities:

$$\mathcal{E}^{s}_{j,x,LR} = \frac{p^x}{p^x - \alpha^x_j - (1-\beta_j(1-\eta_j))\alpha^{ix}_j}$$

$$\mathcal{E}^{d}_{j,x,LR} = -\frac{p^x}{p^y_{ss} - p^x - \alpha^y_j - (1-\beta_j(1-\delta_j))\alpha^{iy}_j}$$

$$\mathcal{E}^{s}_{j,y,LR} = \frac{p^y}{p^y - p^x_{ss} - \alpha^y_j - (1-\beta_j(1-\delta_j))\alpha^{iy}_j}$$

$$\mathcal{E}^{d}_{j,y,LR} = -\epsilon$$

Notice that the short- and long-run demand elasticities for the refined product are constant across time and countries, and are given by the exogenous demand function outlined in Section 3. We report the elasticities in Table 3.

Table 3: Mining and Refining elasticity with respect to prices

	Supply		**Demand**	
	(SR)	(LR)	(SR)	(LR)
Mining				
Net-REE Importers	0.0037	1.79	-0.0044	-2.09
China	0.003	1.41	-0.0031	-1.46
Refining				
Net-REE Importers	0.008	3.81	-0.15	
China	0.0056	2.66	-0.15	

Notes: SR denotes short-run elasticities, while LR denotes long-run elasticities. The SR supply elasticity of mined [refined] products is derived from (9) [(10)], evaluated at 2024 prices and quantities, and is given by $\frac{\partial x}{\partial p^x}\frac{p^x}{x}$ $\left[\frac{\partial y}{\partial p^y}\frac{p^y}{y}\right]$. The SR demand elasticity for mined products is derived from (10) and is given by $\frac{\partial y}{\partial p^x}\frac{p^x}{y}$. The demand elasticity is exogenous and given by ϵ. Similarly, LR elasticities are derived from (11) and (12).

The short-run elasticities of demand and supply are close to zero, indicating a limited ability to adjust quantities for both miners and refiners in the short run. From the refiners' perspective, the rigidity in their short-run supply of refined products also constrains the demand for mined (raw) inputs. Similarly, miners display rigid supply schedules. As a result, the short-run dynamics of the upstream market are characterized by highly inelastic supply and demand functions. Moreover, supply and demand are more rigid in China, relative to other countries, resulting from the stronger cost-advantage of Chinese miners and refiners, thus supporting higher equilibrium levels of output. In the long-run, both mining and refining become significantly more flexible, with greater responsiveness for net-REE importers. Overall, these findings highlight a pronounced distinction between short-run and long-run dynamics in the REE market.

5.2 What are the effects of a potential supply disruption?

Given the strong degree of concentration in both mining and refining markets, we consider a scenario of hypothetical REE market fragmentation in two blocks, with China+, the major producer, refiner and exporter of REE, and the rest of the world operating as two distinct blocks.

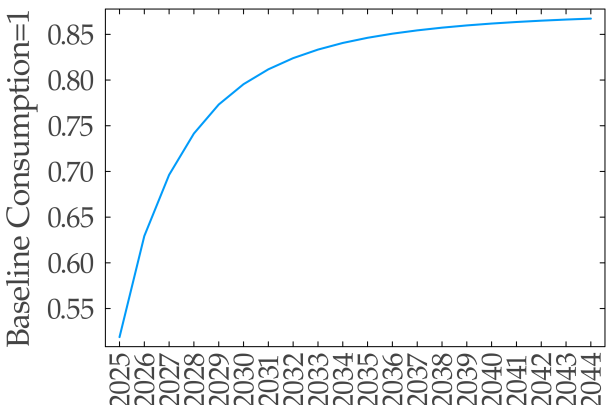
Table 4: Impact of a market fragmentation on net-REE importers (pre-shock quantities=100)

Mining	
China+'s supply of mined product	-80.88
China+'s demand of mined product	-91.67
Excess supply in mining markets outside China+	*+10.78*
Refining	
China+'s supply of refined product	-91.67
China+'s demand of refined product	-50.00
Excess supply in refining markets outside China+	*-41.67*

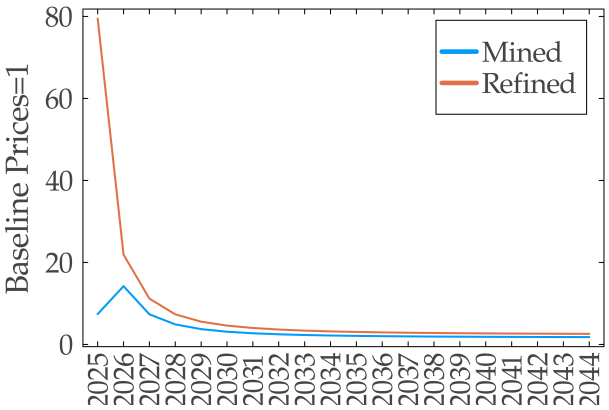
Table 4 describes the first-pass consequences of the shock. On the one hand, in the market for mined products, the impact would generate a positive excess supply, as China is a net importer of mined inputs for refining. This would result in a 10.78% increase in net supply in markets outside China. On the other hand, the impact of the market fragmentation on the refining market would be substantial. As China accounts for around 92% of the global supply of refined products, the shock to pre-shock net importers would be large. At the same time, since China also demands around 50% of refined products, net-REE importers would experience a net supply shock of approximately -42%.

We evaluate the effects of this shock on net-REE importing countries. We consider a scenario in which these economies start from their respective 2024 demand and supply levels and, unexpectedly, the market becomes segmented at time $t = 2025$. As noted above, since the relative production of mined and refined products across these economies outside China is determined by the slope of the marginal CAPEX costs, the impact of the shock is symmetric across all countries. We report the results of this supply disruption scenario in Figure 5.

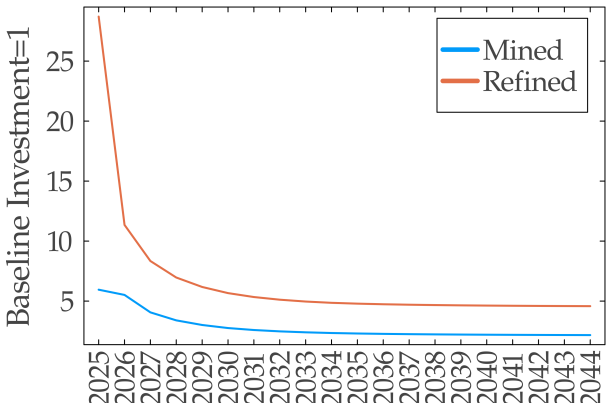
Figure 5: Effects of a full market fragmentation on Global REE markets (on net-REE importers)



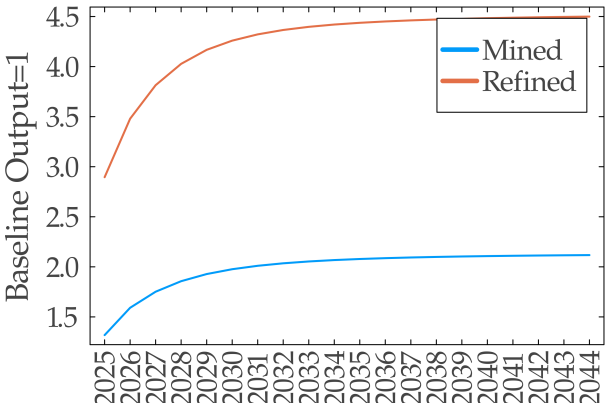
(a) Consumption, refined products



(b) Prices



(c) Investment in Capacity



(d) Output

On impact, the supply disruption causes a sharp increase in prices in both markets, i.e., the market for mined and refined products. In the first year, the price of refined REEs spikes to almost 80 times the baseline price, while mined REE products experience a smaller increase, around 7.4 times the baseline price. The structure of the downstream market plays a key role. Since refineries outside China are less productive than Chinese ones, the shock has a much larger impact on refining than on mining. Additionally, the price of mined products is partially capped by the positive net supply shock in the upstream market, as China is a net importer of raw materials.

The increase in prices plays two roles. First, it reduces demand for refined REE products, which falls by around 48% on impact. Second, it stimulates investment in refining capacity,

leading to a more than threefold increase in the supply of refined products. The expansion in refining, in turn, raises demand for mined inputs, which increases to about 1.3 times its baseline level. As a result, the equilibrium price of mined products also rises on impact, although less than that of refined products. Despite the initial positive net supply shock for miners outside of China, the disruption in the downstream market is large enough to drive up both prices and increase upstream production in order to restore equilibrium in the downstream market. The strong response of prices, combined with the limited adjustment of quantities, highlights the low supply and demand elasticities of the REE market in the short run.

In the long run, CAPEX investment in both upstream and downstream markets gradually expands capacity. As a result, mining (refining) output rises to about 2.1 (4.5) times its pre-shock level, and prices begin to decline relatively quickly. In the upstream market, the equilibrium price falls from 7.4 to 1.7 times the baseline price, remaining about 70% above the baseline. Similarly, in the downstream market, the equilibrium price of refined products declines from 80 to 2.5 times the baseline, i.e., about 150% above baseline. The combination of higher production and lower prices allows final consumers to recover part of the lost demand relatively quickly, which converges to around 89% of its baseline level, implying a long run loss of about 11% of the baseline demand. Contrary to the short run, quantities adjust more flexibly in the long run, highlighting our finding that supply and demand elasticities of the REE market are higher in the long run.

5.3 Industrial Policies

In response to rising vulnerabilities in REE supply, countries and firms are adopting a range of adaptation strategies. *Stockpiling* provides a short-term buffer against disruptions, but does not address underlying structural dependence, while recycling offers longer-term potential, although it cannot yet serve as a primary supply source. *Reshoring* and *import diversification* have emerged as the main medium-term responses, despite uncertain viability given long development timelines, coordination challenges, and potential shortages of skilled labor.

Because reshoring is costly, policymakers must balance efficiency losses in normal times against expected disruption losses in crisis periods. Optimal *de-risking* is best understood as

an insurance policy: the premium paid in normal times (efficiency losses) should be commensurate with the expected damage in crisis times (disruption losses). Moreover, security benefits are likely to exhibit diminishing returns, with the first 10-20 percent increase in de-risking delivering the largest reduction in vulnerability. This means that even modest increases in de-risking can substantially reduce vulnerability to supply disruptions at relatively low efficiency costs (Clayton et al., 2024).

To improve the degree of de-risking, which we define as the total consumption of refined REEs that is either produced at home or from other countries other than the market leader, we ask the model to assess the effects of two industrial policies (investment subsidies and stylized revenue-support policies) applied to refiners, under two implementation scenarios: (1) unilateral action by the United States, in which the policy instruments apply only to U.S.-based producers, and (2) simultaneous action among all importing countries (U.S., EU, Japan, Australia, and other economies), in which instruments are applied uniformly across participating countries. Because trade in the model is frictionless and homogeneous, the resulting country-level de-risking statistics should be interpreted as reduced-form concentration measures rather than literal bilateral sourcing predictions. We focus on refiners only because, as discussed above, a global supply shock primarily affects the downstream segment, while the impact on miners is more limited.[35]

We start by selecting a constant CAPEX subsidy rate (or revenue-support rate) that would allow the U.S., in this example, to reach a 25% level of de-risking by 2035. This is 15 percentage points higher than our baseline and in line with IEA projections which show that, under currently announced projects outside China and stated government policies, de-risking levels outside of China would rise from about 8 percent to roughly 24 percent over the next decade. We then compare the fiscal cost of achieving the same benchmark increase in de-risking for the U.S. by allowing all importer countries to simultaneously implement similar policies. The same kind of exercise with very similar results could have been run focusing on either one of the importing countries of our model. We then repeat the same exercise for a more ambitious target of 50%.

[35]It can be shown that industrial policies targeting upstream producers are ineffective at reducing dependence on Chinese refiners. With downstream capacity remaining constrained, excess supply of mined products would depress both upstream and downstream prices and ultimately benefit Chinese refiners, which operate with higher profit margins in the downstream market. In Appendix B we introduce a 77% CAPEX subsidy to miners, equivalent to our unilateral policy scenario for refiners, and show that refiners' de-risking level does not improve substantially, while generating large fiscal costs.

In the model, the revenue-support instrument is implemented as a proportional sales subsidy to refiners rather than as a literal state-contingent floor that binds only when market prices fall below a trigger. Accordingly, the revenue-support rate for refiners is defined as $s_{jt}^{y} \equiv f_{j}^{y} - 1$, where $f_{j}^{y} \geq 1$ denotes the policy wedge set by the policymaker in country j. This formulation captures the broad idea of downside revenue support for refiners, but it should not be interpreted as a full contractual representation of an offtake agreement or a state-contingent contract. Conversely, the CAPEX subsidy satisfies $s_{jt}^{iy} \in [-1, 0]$.

We next describe how the degree of de-risking is computed. For each country $j \in \{1, \ldots, J\}$ and each period $t \in \{0, \ldots, T\}$, we construct the matrix of net import flows M_t, which collects the net flow of imports of refined REEs from country j to country i. We begin by computing each country's share of global exports as:

$$xs_{j,t} = \frac{\max\left(y_{j,t} - q_{j,t}, 0\right)}{\sum_{i} \max\left(y_{i,t} - q_{i,t}, 0\right)}$$

Given that goods are homogeneous across countries, we then allocate each country's net imports in proportion to each net exporter's share of the world's exports as follows:

$$m_{ij,t} = xs_{j,t} \cdot \max\left(q_{i,t} - y_{i,t}, 0\right)$$

where $m_{ij,t}$ is the generic element of the matrix of net import flows M_t at time t that indicates imports from country j to country i. For each country i, we define the degree of de-risking as:

$$\sigma_{i,t} = 1 - \frac{\max_{j \in \mathcal{J}} m_{ij,t}}{q_{i,t}}$$

where $\max_{j \in \mathcal{J}} m_{ij,t}$ denotes country i's imports from its largest supplier.[36] According to our measure, a self-sufficient country is a country that does not import excessive amount of consumption from any single country. Values of $\sigma_{i,t}$ close to 1 indicate high levels of de-risking, whereas values close to 0 indicate strong dependence on exports from any single country.

Table 5 reports the policy rates used in all eight policy experiments. As expected, more ambi-

[36] We restrict our attention to de-risking from China only, as China represents the largest (and only) net exporter for refined REE products, hence all countries import the most from China.

tious de-risking targets require higher subsidies or stronger revenue-support wedges. However, simultaneous action among various importers does not necessarily imply lower subsidy rates or lower revenue-support wedges. Intuitively, because the U.S. targets refined products produced outside of China, the industry's largest exporting country, it can rely on production from all other participating countries. Since the U.S. is relatively more efficient than other importers, inducing additional production in less efficient countries may require stronger policy support, as is the case for CAPEX subsidies under the 25% de-risking target.

Table 5: Industrial Policies: Subsidy rates and price floors

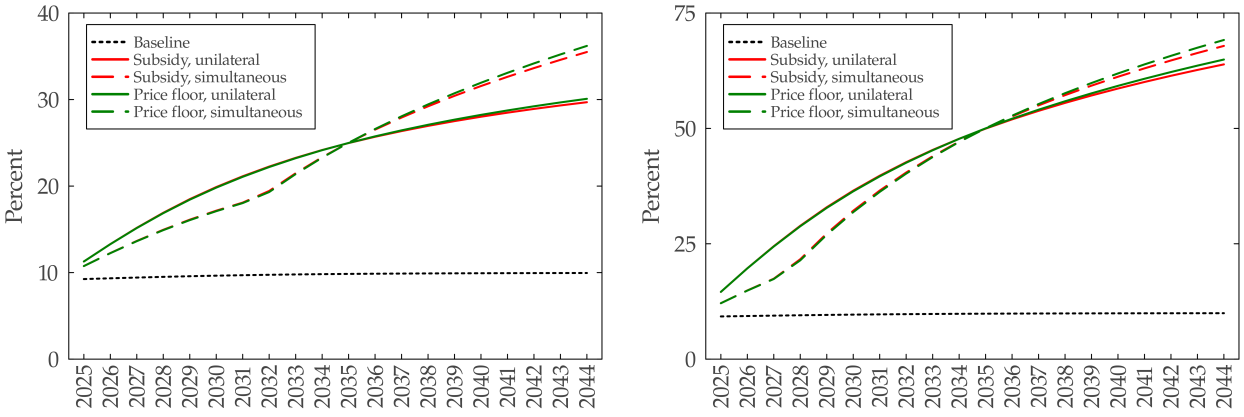
Industrial Policy	**Policy Parameter**	**Target 25%**	**Target 50%**
CAPEX Subsidy, unilateral	s_{jt}^{iy}, $j =$ U.S.	-74.41%	-88.72%
CAPEX Subsidy, simultaneous	s_{jt}^{iy}, $j \neq$ China	-73.97%	-87.91%
Price Floor, unilateral	f_j^y, $j =$ U.S.	2.19	4.08
Price Floor, simultaneous	f_j^y, $j \neq$ China	2.00	3.05

We report the results of the policy experiments in Figure 6. By construction, all policies achieve their target exactly in 2035. For both the 25% and the 50% targets, unilateral policies, regardless of the instrument, allow the U.S. to attain higher pre-2035 de-risking levels than under simultaneous action. In the long-run, however, simultaneous policies outperform unilateral ones in both the 25% and the 50% cases.[37]

Conditional on the degree of simultaneous actions, CAPEX subsidies and the stylized revenue-support policies are broadly equivalent in delivering the desired levels of de-risking over the first 13–15 years.

[37] In Appendix B we decompose the difference between de-risking levels achieved under unilateral and simultaneous policies. We show that, under simultaneous policies, the degree of de-risking is initially lower than unilateral policies due to stronger imports from China. After around 6 years, the U.S. start substituting China with the rest of the world, accelerating the improvement in de-risking.

Figure 6: U.S. Degree of de-risking for different targets



(a) 25% Target (b) 50% Target

While the degree of de-risking is independent from the policy instrument, the fiscal cost of these industrial policies differs substantially. Figure 7 reports the fiscal cost across all policy experiments. Fiscal costs Φ_{jt} are expressed relative to baseline consumption as follows:

$$\Phi_{jt} = \begin{cases} \dfrac{s_{jt}^{iy} c_j^{iy}(i_{jt}^y)}{p_{t,\text{BAS.}}^y q_{jt,\text{BAS.}}} & \text{if CAPEX subsidy} \\ \dfrac{p_t^y (f_j^y - 1) y_{jt}}{p_{t,\text{BAS.}}^y q_{jt,\text{BAS.}}} & \text{if revenue support} \end{cases}$$

where the subscript "BAS." indicates the baseline scenario. Three main results emerge:

(i) **For a given policy instrument, simultaneous action reduces the fiscal cost to achieve a given level of de-risking fo the U.S. and all participating countries.** As all net REEs importers increase their output, the U.S. can attain higher de-risking levels with a smaller expansion in domestic production and relying more on imports from other participating countries, thereby limiting fiscal costs even when policy rates are comparable (or slightly higher). In a similar fashion, as simultaneous action increases global REE output more than unilateral action, part of the increment is absorbed by consumption in all other countries, who successfully manage to partially de-risk their supply chain.

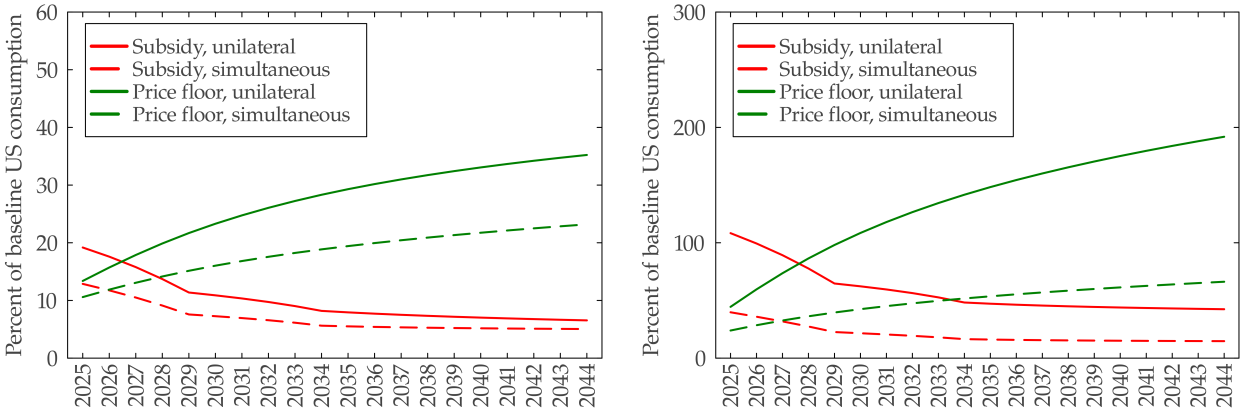
(ii) **The fiscal cost of CAPEX subsidies is initially higher than that of the revenue-support**

policy, but substantially lower in the long run. On the one hand, investment precedes production during growth phases. Therefore, CAPEX subsidies frontload fiscal costs in the early years, with lower costs later on as investment needs decline. On the other hand, the price floor backloads fiscal costs: as production and prices rise over time, fiscal costs increase and remain elevated as the economy converges towards a new steady state.

(iii) **The fiscal cost increases faster than the increase in achieved de-risking levels.** Taking unilateral revenue support as a reference, the cost of achieving 25% de-risking levels by 2035 is about 13.4% of baseline consumption in 2025, whereas the cost exceeds 44.5% if the U.S. was targeting 50% by 2035. In the long-run, the fiscal cost of the unilateral revenue-support policy stabilizes around 41.6% of baseline consumption for a 25% target, but rises to over 269% for the 50% target. Hence, doubling the de-risking target more than doubles the fiscal cost. Similar results are observed also for the other policy instruments.

Overall, for a 25% de-risking target, the total fiscal cost of industrial policies over the period 2025–2035 is large in terms of market size. CAPEX subsidies amount to 134% of the annual U.S. REE market under unilateral action and 90% under simultaneous action among various importers. The stylized revenue-support policies are significantly more expensive, reaching 248% under unilateral policies and 172% under simultaneous policies. Fiscal costs are even higher when targeting 50% de-risking benchmarks.

Figure 7: U.S. Fiscal Costs of Increased De-Risking



(a) 25% Target (b) 50% Target

The Impact of Industrial Policies on the Global REE Market - While in our example these industrial policies improve U.S. de-risking levels, we also examine their spillover effects on other net-REE importing countries. As described above, under simultaneous action all of these participating economies adopt the same policy instrument and rate. Because the strategy of net-REE importers emphasizes *de-risking*, we focus on aggregate net-REE importers outcomes, rather than the outcome of the single country alone. Figure 8 reports the impact of CAPEX subsidies to refiners on China and other economies. The left-hand column shows results for policies targeting a 25% U.S. de-risking level by 2035, while the right-hand column reports results for the 50% target. We examine effects on mining and refining output, consumption of refined products, and prices:

(a) *Mining* - Under a 25% target, unilateral subsidies moderately increase mining output in both China and other economies, with a slightly larger effect outside China (+0.3%) than in China (+0.26%). Under a 50% target, unilateral subsidies increase Chinese mining output by 0.66%, while output in net importing countries increases by 0.79%. Under simultaneous action, both blocks experience larger increases in mining output due to stronger demand from refiners. Chinese mining output increases by 1.44% (2.8%) in the long-run for the 25% (50%) target, while output net importing countries increases by 1.72% (3.3%). Overall, industrial policies targeting refiners generate positive spillovers on miners in all countries.

(b) *Refining* - In contrast to mining, policies targeting refiners have diverging effects across regions. In China, refining output declines by 2.5% under unilateral subsidies and by 14.8% under simultaneous action for a 25% target. The effect is stronger under a 50% target, with declines of 6.8% and 27.7%, respectively. By contrast, refining output outside China increases substantially: by 25.9% (70.8%) under unilateral action and by 154.7% (290%) under simultaneous policies for the 25% (50%) de-risking target.

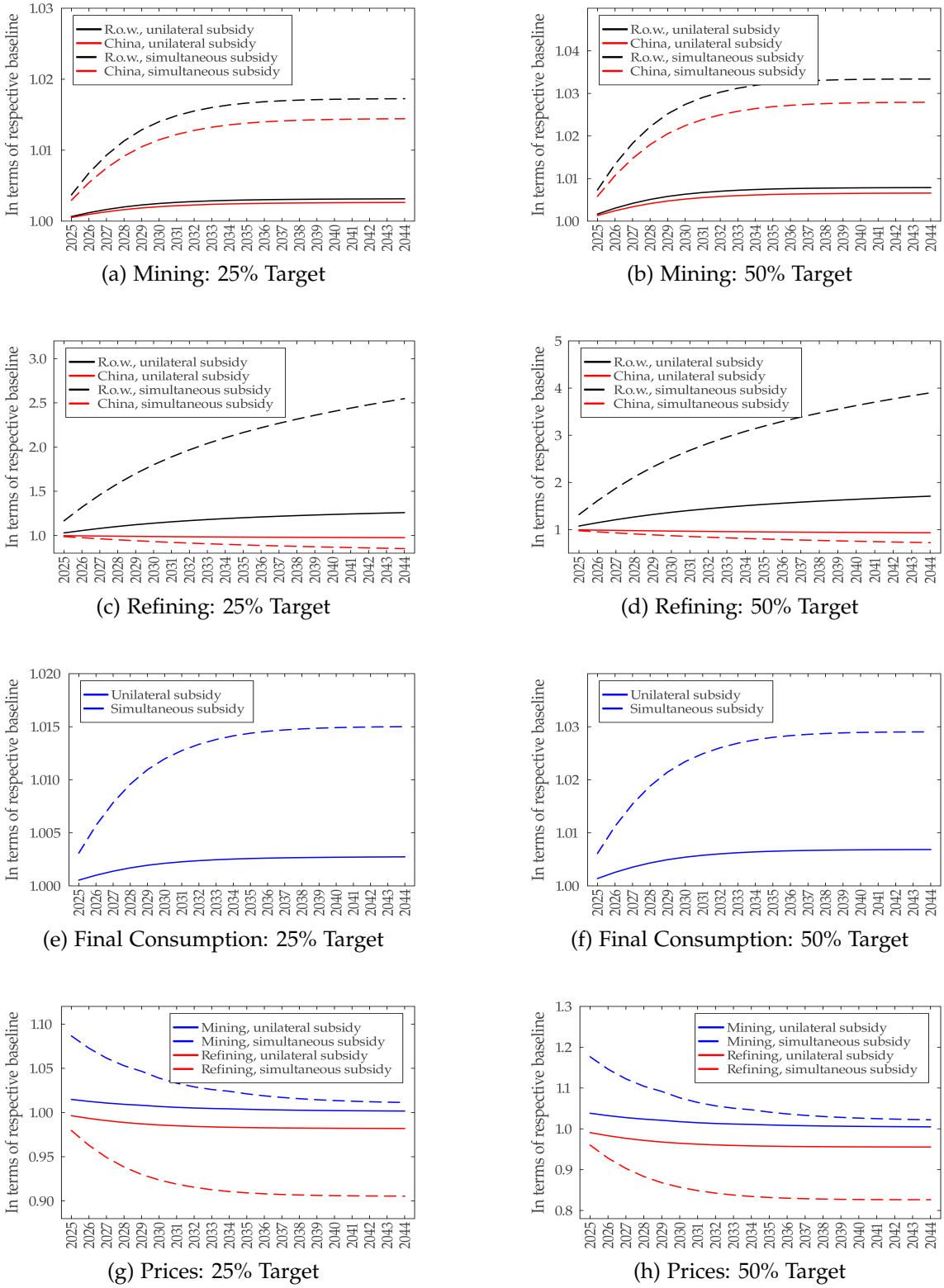
(c) *Consumption* - Industrial policies have relatively small effects on consumption. All countries are symmetrically affected by the policies, and global consumption increases by 0.27% under unilateral action with a 25% target, and by 1.5% under simultaneous policies. For a 50% de-risking target global consumption increases by 0.69% (2.91%) under unilateral (simultaneous) action.

(d) *Prices* - Price dynamics reflect the changes in mining and refining. Under unilateral subsidies, mining prices initially rise by 1.48% (3.82%) and settle at +0.17% (+0.49%) in the long-run for the 25% (50%) target. Under simultaneous subsidies, mining prices rise by 8.66% (17.66%) on impact and converge to +1.13% (+2.22%) in the long-run for the 25% (50%) target. In contrast, refining prices decline.

Under unilateral U.S. policies, U.S. de-risking increases, while that of other net importers remains broadly unchanged or even slightly declines. In contrast, simultaneous policies among importers allow both the U.S. and the other importing countries to increase their degree of de-risking. As shown in Figure 9, both simultaneous CAPEX subsidies and revenue-support policies improve the degree of de-risking for Japan and the EU. Since both start from relatively lower levels than the U.S., 6% and 8.9%, respectively, simultaneous actions allow them to achieve substantially higher independence relative to their baseline. While the U.S. attains 25% de-risking levels by 2035, the EU reaches 17.1% and Japan 23.1%. Relative to the simultaneous benchmark, unilateral U.S. policies leave the EU and Japan less de-risked because negative price spillovers crowd out part of the production response elsewhere; relative to their own baselines, however, the declines remain modest. Analogous results are observed for the simulation with a higher benchmark of 50% de-risking in the U.S..

Industrial policies also generate notable differences in fiscal costs across countries. Figure 10 reports the fiscal costs of simultaneous policies for the U.S., EU, and Japan. Simultaneous action allows the U.S. to shift part of the fiscal burden onto other net-REE importing countries. Focusing on the 25% target, the cost of CAPEX subsidies is nearly as high in Japan as in the U.S., while it is significantly lower in Europe. This reflects differences in refining activity: fiscal costs are higher in countries with larger refining sectors (such as the U.S. and Japan) and lower where refining activity is more limited. This pattern holds for both policy instruments and for the 50% de-risking target.

Figure 8: Impact of Industrial Policies: CAPEX Subsidies



(a) Mining: 25% Target

(b) Mining: 50% Target

(c) Refining: 25% Target

(d) Refining: 50% Target

(e) Final Consumption: 25% Target

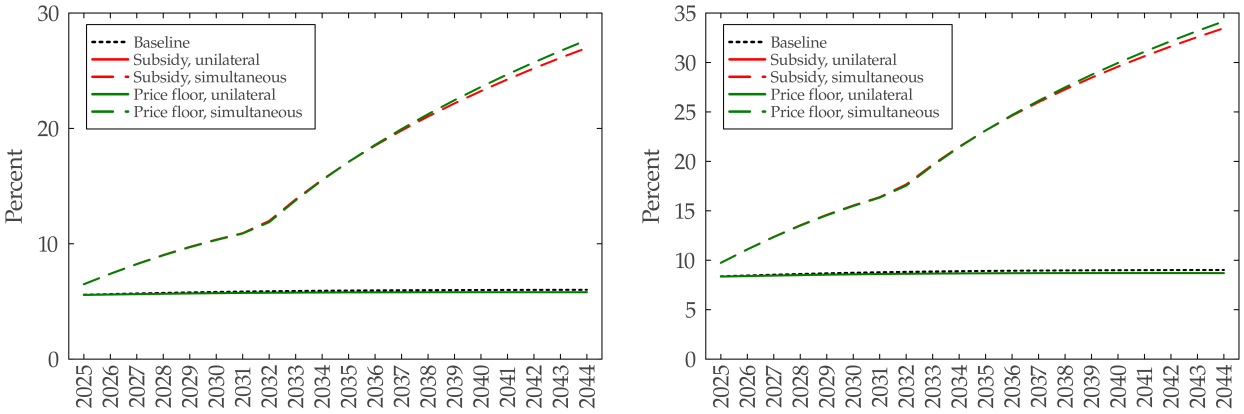
(f) Final Consumption: 50% Target

(g) Prices: 25% Target

(h) Prices: 50% Target

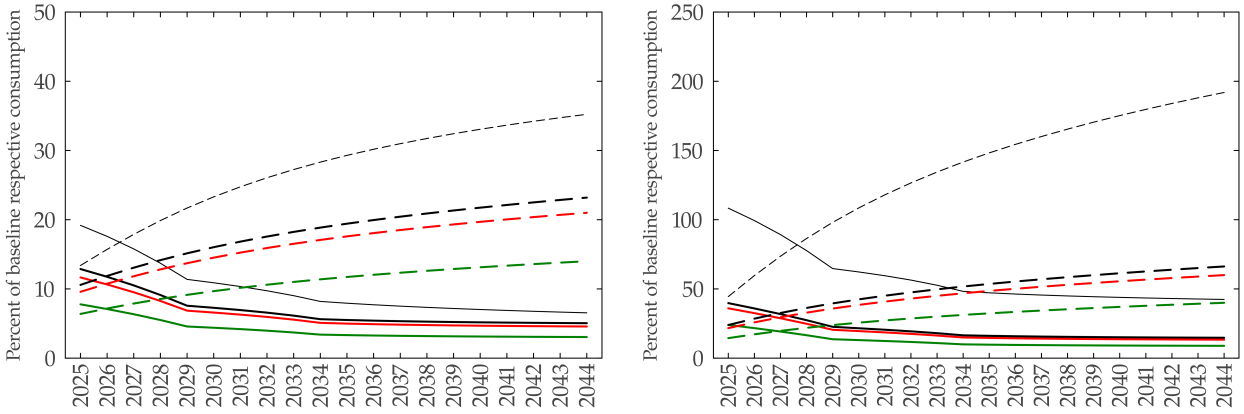
Note: Mining (refining) values refer to quantities of mined (refined) output produced in China and in the rest of world (RoW), respectively. All values are expressed relative to their corresponding baseline levels.

Figure 9: Degree of De-Risking for other economies (25% U.S. target)



(a) European Union (b) Japan

Figure 10: Fiscal Cost of Increased De-Risking: Simultaneous Policies

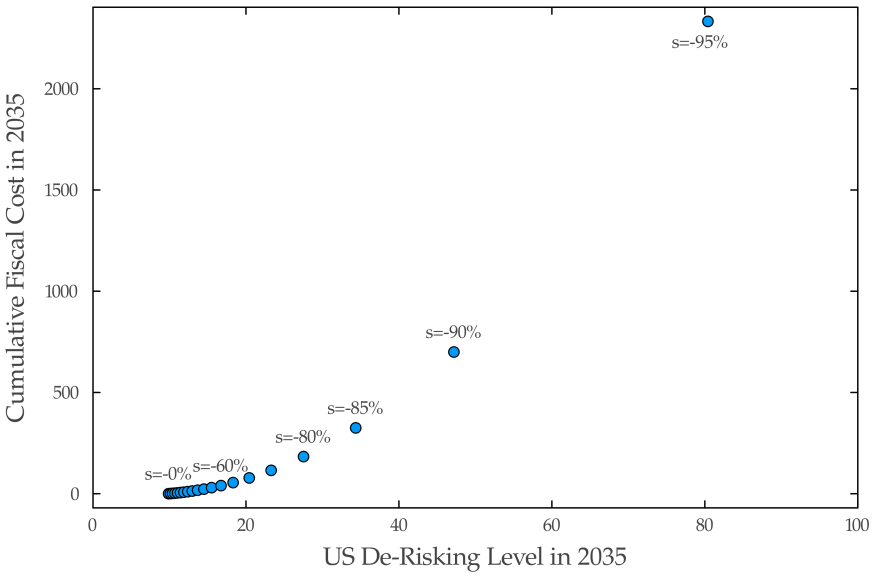


(a) 25% Target (b) 50% Target

Note: United States (black), European Union (green), Japan (red). Simultaneous CAPEX subsidy (solid), simultaneous revenue support (dashed). Thin black lines denote U.S. fiscal costs of unilateral subsidies/revenue support.

The Increasing Cost of Industrial Policies - As noted above, achieving a 50% level of de-risking is significantly more expensive than reaching the 25% target. To examine this, we study the level of de-risking attained in 2035 and the corresponding cumulative fiscal cost for the U.S. under unilateral CAPEX subsidies. The results are reported in Figure 11.

Figure 11: Cost of of increased de-risking Targets



Note: The fiscal cost is computed as: $\sum_{t=2025}^{2035} \frac{s^{iy}_{\text{US},t} c^{iy}_{\text{US}}(i^{y}_{\text{US},t})}{p^{y}_{t,\text{BAS.}} q_{\text{US},t,\text{BAS.}}}$. The results reported are for levels of subsidies that range from 0 to -95%. The -100% case has been excluded for illustration purposes.

For low CAPEX subsidy rates the achieved level of de-risking is low, as is the associated fiscal cost. Higher subsidy rates are required to attain higher levels of de-risking. For example, subsidy rates below 60% allow the U.S. to achieve at most about 18% de-risking levels. Further increases in the subsidy rate lead to higher levels of de-risking. In particular, increasing the subsidy rate from 80% to 90% raises de-risking levels by over 20 percentage points, while moving from 85% to 95% raises it by approximately 45 percentage points. These results suggest that the marginal benefit of increasing the subsidy rate rises with the level of the subsidy itself.

The associated fiscal cost also increases. While low subsidy rates generate moderate de-risking levels at relatively low fiscal cost, the cost increases more than proportionally at higher levels of de-risking. We further document this pattern by computing the elasticity of the fiscal costs with respect to de-risking levels for different subsidy levels. First, we construct the cumulative fiscal cost as:

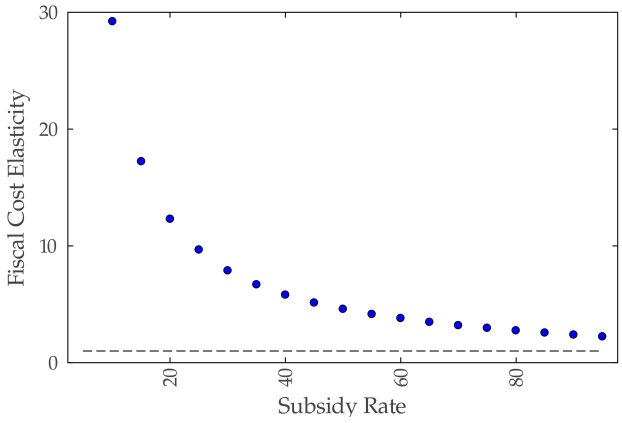
$$\mathcal{C}_{\text{US},2035} \equiv \sum_{t=2025}^{2035} \frac{s^{iy}_{\text{US},t} c^{iy}_{\text{US}}(i^{y}_{\text{US},t})}{p^{y}_{t,\text{BAS.}} q_{\text{US},t,\text{BAS.}}}$$

from 2025 to 2035. Then, we compute the elasticity as:

$$\mathcal{F}_{\text{US,2035}} \equiv \frac{\partial \log(\mathcal{C}_{\text{US,2035}})}{\partial \log(\sigma_{\text{US,2035}})}$$

Figure 12 reports the elasticity of fiscal costs with respect to de-risking levels. The elasticity is above 1 (the dashed black line) for all subsidy rates, which indicates that fiscal cost rises more than proportionally with the attained de-risking rate over the range shown.

Figure 12: Fiscal Cost Elasticity



Note: Each dot represents the elasticity of fiscal cost with respect to the attained de-risking rate (y-axis) for a given subsidy rate (x-axis). Elasticity values above 1 indicate that, locally, fiscal cost is increasing more than proportionally with the attained de-risking rate.

6 Conclusion

This paper shows that disruptions to REE supplies could substantially affect supply chains. Avoiding trade tensions and restrictions remains the first-best outcome to promote steady REE supply. Model-based analysis suggests that de-risking supply chains through targeted industrial policies is fiscally costly. However, costs are lower if de-risking is pursued by various importers simultaneously and if policy instruments directly target the expansion of new production capacity. Focusing on CAPEX subsidies and price floor mechanisms, we found that simultaneous action allows participating countries to achieve higher levels of de-risking at relatively moderate fiscal costs, particularly when CAPEX subsidies are implemented. Finally, we showed that more ambitious de-risking targets become increasingly costly, with fiscal costs rising exponentially as

de-risking targets increase.

Future research could take a more granular view of the rare earth element complex, which, after all, consists of 17 distinct yet chemically related elements, with the aim of developing a framework that distinguishes between heavy (HREE) and light (LREE) elements and embeds these distinctions in the modeling of supply constraints. Additional policies – like stockpiling or re-shoring – could also be analyzed and the group of producer countries could be enlarged beyond China.

References

Alfaro, L., Fadinger, H., Schymik, J., and Virananda, G. (2025). Trade and industrial policy in supply chains: Directed technological change in rare earths. Technical Report 33877, National Bureau of Economic Research, Cambridge, MA.

Alonso, E., Pineault, D. G., Gambogi, J., and Nassar, N. T. (2023). Mapping first to final uses for rare earth elements, globally and in the united states. *Journal of Industrial Ecology*, 27(1):312–322.

Anderson, S. T., Kellogg, R., and Salant, S. W. (2018). Hotelling under pressure. *Journal of Political Economy*, 126(3):984–1026.

Arezki, R., van der Ploeg, F., and Toscani, F. (2019). The shifting natural wealth of nations: The role of market orientation. *Journal of Development Economics*, 138:228–245.

Baquie, S., Huang, Y., Jaumotte, F., Kim, J., Machado Parente, R., and Pienknagura, S. (2025). Industrial policies: Handle with care. Technical Report SDN/2025/002, International Monetary Fund, Washington, DC.

Bedford, J. (2025). Rare earths and industry: Why dependence on china endures. Technical Report 1843, East Asian Institute, National University of Singapore, Singapore.

Bogmans, C., Jerez-Osses, M., Miranda-Pinto, J., and Natal, J.-M. (2026). Macroeconomic effects of rare earths supply chain disruptions. *IMF Working Paper YY/2026*.

Chen, Q. (2025). Digging up the value chain: Mineral export restrictions and industrial upgrading. Technical report, Working Paper.

Clayton, C., Maggiori, M., and Schreger, J. (2024). A theory of economic coercion and fragmentation. Technical Report 33309, National Bureau of Economic Research, Cambridge, MA.

Clayton, C., Maggiori, M., and Schreger, J. (2026). A framework for geoeconomics. *Econometrica*, 94(1):105–136.

Dürr, B. and Heilmann, S. (2025). *Geoeconomics: How Geopolitical Rivalries Reshape Global Markets*. GeoEcon Publishing, Berlin.

Gielen, D. and Lyons, M. (2022). Critical materials for the energy transition: Rare earth elements. Technical report, International Renewable Energy Agency, Abu Dhabi. Technical Paper 2/2022.

Graedel, T. E., Harper, E. M., Nassar, N. T., and Reck, B. K. (2015). On the materials basis of modern society. *Proceedings of the National Academy of Sciences of the United States of America*, 112(20):6295–6300.

International Energy Agency (2025). Global critical minerals outlook 2025. Technical report, International Energy Agency, Paris. Licence: CC BY 4.0.

Kee, H. L. and Xie, Q. (2025). Nickel, steel and cars: Unintended consequences of export restrictions. Policy Research Working Paper 11249, World Bank, Washington, DC.

Kellogg, R. (2024). The end of oil. Technical Report 33207, National Bureau of Economic Research, Cambridge, MA.

Kooi, O. (2025). Power and resilience: An economic approach to national security policy. Job Market Paper, University of Chicago.

LSEG Refinitiv Workspace (2024). Rare earth oxide prices: Praseodymium, neodymium, gadolinium, yttrium, cerium, lanthanum, samarium, terbium, dysprosium, and europium. Prices sourced from Refinitiv Workspace for: Praseodymium Oxide (Pr6O11/TREO), Neodymium Oxide (Nd2O3/TREO 99.0–99.9%), Gadolinium Oxide (Gd2O3/TREO), Yttrium Oxide (Y2O3/TREO 99.995–99.99), Cerium Oxide (CeO2/TREO 99.5–99.9%), Lanthanum Oxide (La2O3/TREO), Samarium Oxide (Sm2O3/TREO 99.5–99.9%), Terbium Oxide (Tb4O7/TREO 99.95–99.99%), Dysprosium Oxide (Dy2O3/TREO 99.5–99.9%), and Europium Oxide (Eu2O3/TREO 99.95–99.9%).

Ministry of Commerce of the People's Republic of China (2025). Announcement no. 18 of 2025: Decision to implement export control on some medium and heavy rare earth related items. Beijing. Accessed: 2026-05-15.

Morgan Stanley Research (2025). Mapping a potential ex-china rare earths supply chain. Technical report, Morgan Stanley, New York. Metals & Mining Research, June 25.

Nassar, N. T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., Bird, L., and Pineault, D. (2020). Evaluating the mineral commodity supply risk of the u.s. manufacturing sector. *Science Advances*, 6(8):eaay8647.

Nassar, N. T., Du, X., and Graedel, T. E. (2015). Criticality of the rare earth elements. *Journal of Industrial Ecology*, 19(6):1044–1054.

Nassar, N. T., Lederer, G. W., Padilla, A. J., Gambogi, J., Cordier, D. J., Brainard, J. L., Lessard, J. D., and Charab, R. (2023). Rock-to-metal ratios of the rare earth elements. *Journal of Cleaner Production*, 405:136958.

O'Brien, T. M. and Alonso, E. (2025). A simplified rare earth element mining project cost estimator—a new tool for evaluating future mine supply. *Mineral Economics*, 38(2):237–252.

Shao, L., Feng, K., Wu, Z., Chen, Z., Ge, J., Chen, G.-Q., Chen, B., Zhang, B., Li, J., and Chen, W.-Q. (2026). Tracing China's unseen rare earth exports that sustain global consumption. *Cell Reports Sustainability*, 3(1):100553.

Shojaeddini, E., Alonso, E., Nassar, N. T., Pineault, D. G., Allen, S. M., Brainard, J. L., McCaffrey, D. M., O'Brien, T. M., Padilla, A. J., and Ryter, J. W. (2025). Understanding market sensitivity: estimation of supply and demand elasticities for non-fuel minerals. *Mineral Economics*, 38(4):985–996.

S&P Global Market Intelligence (2026a). Capital iq office screener tool. https://www.capitaliq.spglobal.com/web/client?auth=inherit#office/screener?perspective=266637. Accessed via Capital IQ web platform. Used for screening companies by key words in bussines description and geographic location. Accessed: 2026-02-02.

S&P Global Market Intelligence (2026b). Lanthanides development studies dataset. S&P Capital IQ Platform. Accessed via Capital IQ industry development studies. Contains project-level data on lanthanide mining and processing. Accessed: 2026-02-02.

U.S. Department of Energy (2022). Rare earth permanent magnets supply chain deep dive assessment. Technical report, U.S. Department of Energy. Response to Executive Order 14017, "America's Supply Chains", February 24.

U.S. Geological Survey (2025). Mineral commodity summaries 2025. Technical report, U.S. Geological Survey.

U.S. Geological Survey (2026). Rare earths statistics and information. Statistics and information on the worldwide supply, demand, and flow of rare earth elements.

APPENDIX

A Model calibration and incentive price methodology

This section documents the data construction and project-level methodology used to calibrate the cost intercept parameters described in Section 4.3. The analysis is based on a bottom-up reconstruction of production, cost, and revenue characteristics for individual rare earth mining (plus processing) projects outside China. These project-level estimates are used to derive the incentive prices employed in Section 4.3 and to construct the economic supply curve shown in Figure 13.

Project scope and coverage. The dataset is constructed from a mine-by-mine assessment of rare earth projects located in Australia, Sub-Saharan Africa, Brazil, Canada, Greenland, Sweden, and the United States. Projects are included only where sufficient public documentation is available, such as technical reports, economic assessments, and prefeasibility or feasibility studies. These documents were identified primarily through the S&P Capital IQ Pro database and supporting project disclosures, occasionally supplemented with more recent publicly available information. The resulting dataset covers 21 non-Chinese projects with sufficient cost, production, and technical information to reconstruct project-level economic metrics.

Manual reconstruction of production profiles. For each project, technical documentation was manually reviewed to extract total rare earth oxide (TREO) production volumes, reported oxide distributions, and annual production quantities for individual rare earth oxides. These data were then used to identify the elements and corresponding annual production volumes that are economically relevant for the incentive price calculations.

Treatment of non-REE revenues. Where applicable, project documentation reports additional by-product revenues from non-rare earth elements. When detailed production data were available, annual volumes of these non-REE minerals were multiplied by corresponding commodity prices to estimate associated revenue streams. In some cases, projects report only nominal annual

revenue figures for non-REE minerals, which were incorporated directly into the revenue calculations. However, the incentive price used to construct the supply curve in Figure 13 excludes non-REE revenues so that the break-even condition is determined solely by rare earth project economics.

Capital expenditure. Initial capital expenditures (CAPEX) were taken directly from project documentation. Where reported, sustaining capital expenditures were also included.

Operating expenditure. Operating costs (OPEX) were reconstructed from project documentation using one of three approaches depending on data availability. First, where total life-of-mine operating costs were reported, average annual OPEX was calculated as total life-of-mine operating costs divided by the expected mine lifespan. Second, where studies directly reported an average annual operating expense, this value was used as stated. Third, where operating costs were reported as a unit cost (US$ per kilogram of TREO), annual OPEX was calculated by multiplying the reported unit cost by average annual TREO production.

Inflation adjustment and discounting. All monetary values were converted to a common 2024–25 cost basis using a constant annual inflation rate of 2%. In addition, a uniform real discount rate of 8% was applied across all projects. These adjustments were applied consistently to CAPEX, OPEX, and revenue components in order to ensure comparability across projects with feasibility studies produced in different years.

Project classification and realized price factors. Projects were grouped into two categories: those producing mixed rare earth chemical products and those producing separated rare earth oxides. Projects producing mixed rare earth chemical products were assigned a realized price factor of 62.5%, while projects producing separated rare earth oxides were assigned a factor of 90%. These factors capture the difference in realized value between partially processed intermediate products and more refined separated oxides, and ensure that differences in processing depth are reflected consistently in project revenues.

Incentive price definition and break-even condition. For each project, we compute an NdPr-equivalent production metric by converting reported rare earth element revenues into an equivalent quantity expressed in NdPr terms. Specifically, we use all revenue information available in project economic documents (e.g., feasibility studies, economic analyses). For some projects, this consists only of revenues from neodymium, praseodymium, dysprosium, and terbium, while for others it covers a broader set of rare earth elements (e.g., Lanthanum, Cerium, Gadolinium, Yttrium, Samarium, Europium). We aggregate these revenues and divide by the 2024 average NdPr oxide price, yielding an implied NdPr-equivalent production capacity:

$$q^{\text{NdPr}} \equiv \frac{\sum_i p_{o,i}\, q_{o,i}}{p_o^{\text{NdPr}}} \tag{21}$$

This normalization converts a project's multi-element revenue stream into a single NdPr-equivalent production metric, effectively capturing the contribution of all reported rare earth elements into a common NdPr-based quantity.[38] The net present value of a representative project can be written as:

$$\text{NPV}(p) = \sum_{t=1}^{T} \left(p\, q^{\text{NdPr}} + \text{Rev}^{\text{nREE}} - \text{OPEX} \right) \frac{1}{(1+r)^t} - \text{CAPEX} \tag{22}$$

where OPEX denotes total cash operating costs, CAPEX measures initial capital expenditures, Rev^{nREE} represents annual revenues from non-REE minerals (e.g., gallium), r is the discount rate, and T is the project life. Prices and quantities are assumed constant over time. Setting NPV $= 0$ and solving for p yields the incentive price:

$$p^* = \frac{\text{CAPEX} + \Omega \cdot \left(\text{OPEX} - \text{Rev}^{\text{nREE}} \right)}{\Omega \cdot q^{\text{NdPr}}} \tag{23}$$

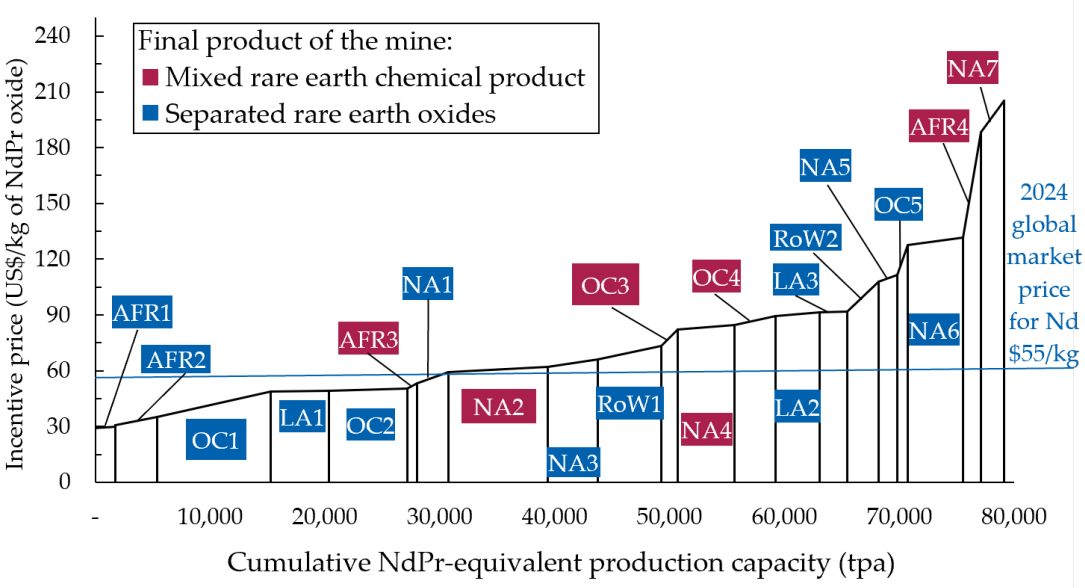
where $\Omega \equiv \sum_{t=1}^{T} \frac{1}{(1+r)^t}$ is the annuity factor. The incentive price p^* thus defines the minimum NdPr oxide price at which projected discounted cash flows recover the initial capital outlay, making the project economically viable.

[38] Implicitly, the framework assumes that relative price ratios across elements remain fixed at their 2024 benchmark levels, so that a change in the NdPr price is representative of a proportional change across the rare earth price complex. While co-movement across elements is imperfect in practice, this assumption provides a tractable single-price metric for comparing projects across a heterogeneous deposit base.

Construction of the economic supply curve. Using the project-level incentive prices defined in equation (23), projects are ranked in ascending order of break-even cost and aggregated cumulatively according to their production capacity. The horizontal axis of Figure 13 reports cumulative NdPr-equivalent production capacity in tons per annum, constructed by converting total project revenues into an equivalent quantity expressed in NdPr terms, while the vertical axis reports the corresponding incentive price in US$/kg of NdPr oxide. Both quantities and prices are therefore expressed in NdPr terms.[39] This procedure produces a stepwise economic supply curve that preserves project-level resolution while illustrating the cost distribution of potential non-Chinese rare earth supply. Project labels identify regions, including AFR (Africa), LA (Latin America), NA (North America), OC (Oceania), and RoW (rest of the world).

[39]NdPr-equivalent production capacity is derived using the identity $\sum_i p_i q_i = P_{M2} \cdot Q_{M2}$, where $\sum_i p_i q_i$ denotes total project revenues across all reported rare earth elements and P_{M2} is the NdPr oxide price. Rearranging yields $Q_{M2} = \frac{\sum_i p_i q_i}{P_{M2}}$, where Q_{M2} represents the NdPr-equivalent production capacity for each project. This transformation converts each project's multi-element output into a single quantity expressed in NdPr terms by scaling total revenues by a common benchmark price. It facilitates comparability across projects because rare earth operations differ substantially in their element mix (e.g., relative shares of Nd, Pr, Dy, Tb versus lower-value elements such as La and Ce) and in how outputs are reported in project disclosures. Expressing output in NdPr-equivalent units converts these different production profiles into a common NdPr-based quantity, allowing projects to be compared on the same economic footing.

Figure 13: Economic Supply Curve for Rare Earth Elements

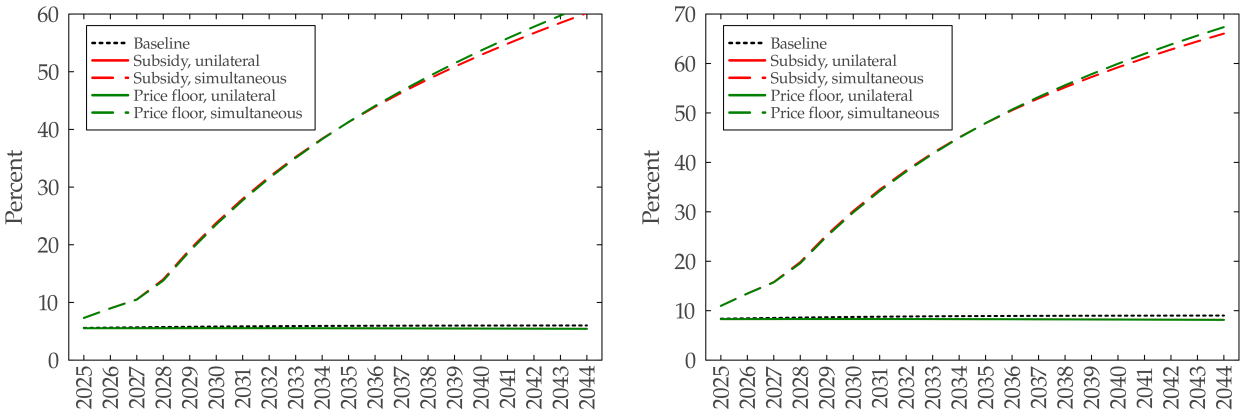


Sources: LSEG Refinitiv Workspace (2024); S&P Global Market Intelligence (2026b); and IMF staff calculations.

Note: The x-axis measures cumulative NdPr-equivalent production capacity in tons per annum (tpa), constructed by converting total project revenues into an equivalent quantity expressed in NdPr terms. The y-axis measures the incentive price in US$/kg of NdPr oxide. Thus, both quantities and prices are expressed in NdPr terms. The horizontal line represents the 2024 global market price of Nd at US$55/kg. AFR = African mines; LA = Latin American mines; NA = North American mines; OC = mines in Oceania; RoW = mines in the rest of the world. The number after each regional abbreviation ranks mines within that region by incentive price. Colors indicate the final product of the mine: mixed rare earth chemical products or separated rare earth oxides.

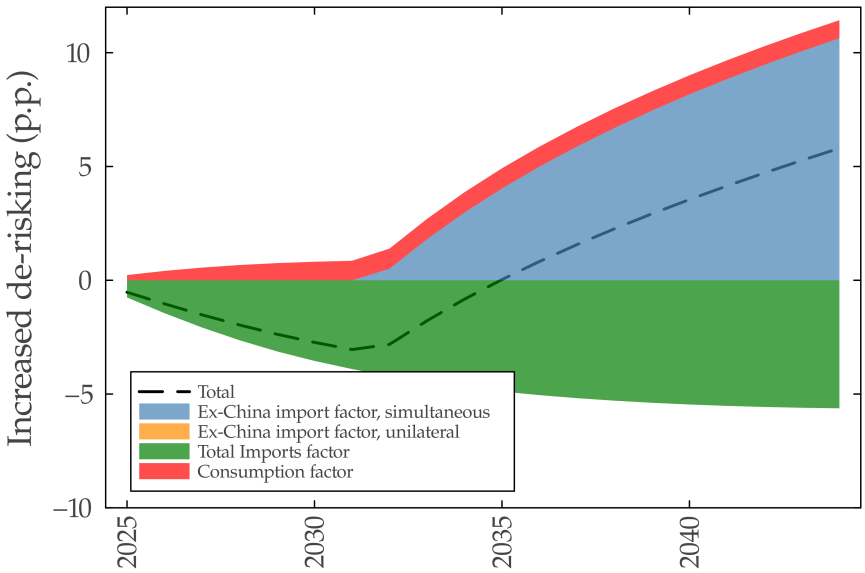
B Additional Charts

Figure 14: Degree of de-risking for other economies (50% U.S. target)



(a) European Union (b) Japan

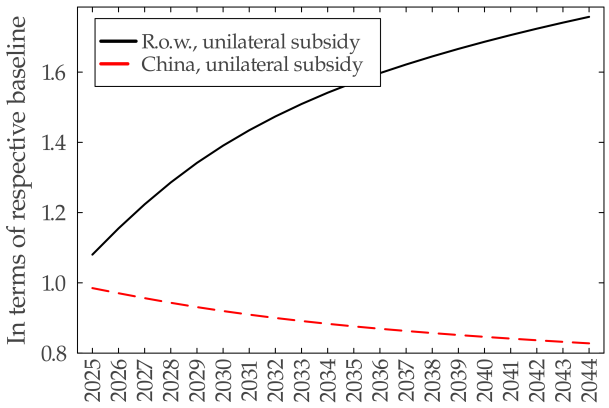
Figure 15: Increased De-Risking Level Decomposition (Simultaneous vs Unilateral, 25% Target)



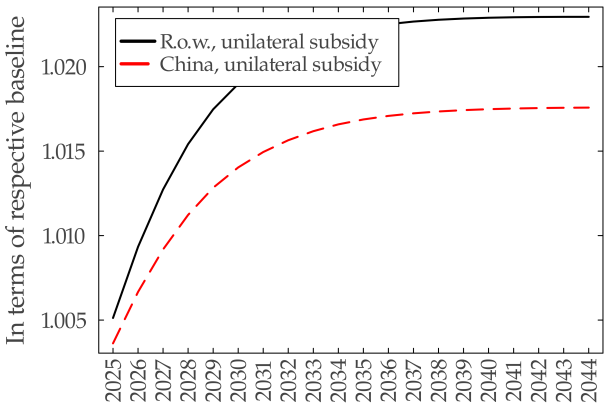
U.S. de-risking decomposition:

$$\sigma^{SI}_{i,t} - \sigma^{UN}_{i,t} = \underbrace{\frac{\sum_j m^{SI}_{ij,t} - \max_j m^{SI}_{ij,t}}{q^{UN}_{i,t}}}_{\text{ex-China imports, simu.}} - \underbrace{\frac{\sum_j m^{UN}_{ij,t} - \max_j m^{UN}_{ij,t}}{q^{UN}_{i,t}}}_{\text{ex-China imports, uni.}} - \underbrace{\frac{\sum_j m^{SI}_{ij,t} - \sum_j m^{UN}_{ij,t}}{q^{UN}_{i,t}}}_{\text{Total imports factor}} + \underbrace{\max_j m^{SI}_{ij,t} \left(\frac{q^{SI}_{i,t} - q^{UN}_{i,t}}{q^{UN}_{i,t} q^{SI}_{i,t}} \right)}_{\text{Increased consump. factor}}$$

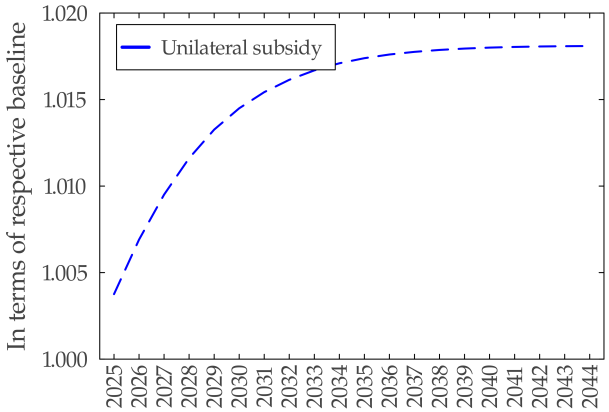
Figure 16: Unilateral CAPEX Subsidy to Miners (74% subsidy rate)



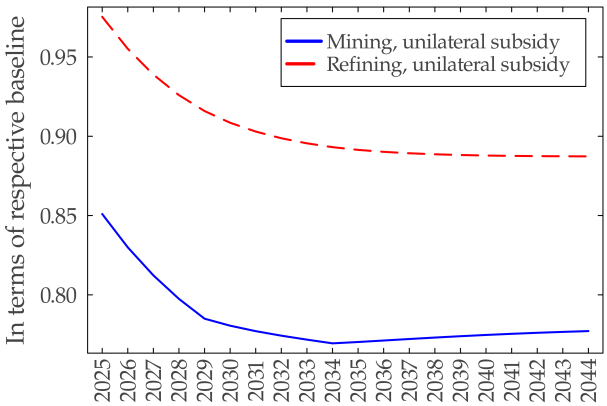
(a) Mining



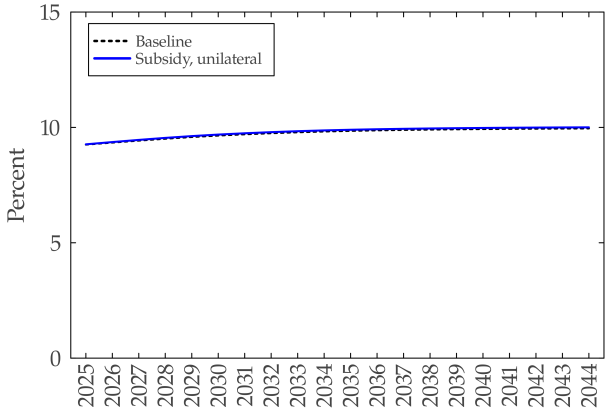
(b) Refining



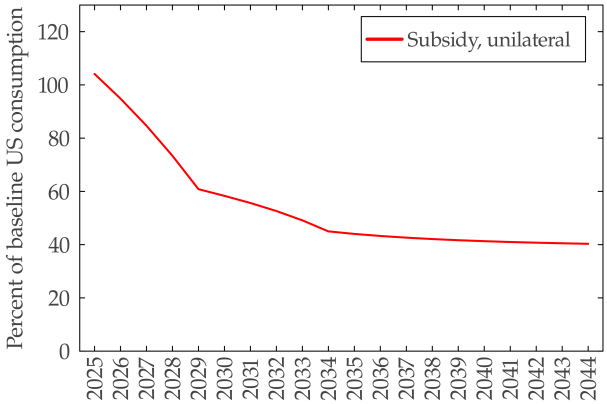
(c) Final Consumption



(d) Prices



(e) Refiners' de-risking



(f) Fiscal Cost



PUBLICATIONS

Industrial Policy and Supply Chain Bottlenecks in Critical Minerals: Evidence from Rare Earth Elements

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